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SYNOPTICAL AND TOPICAL

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OF

A. I. E. E. TRANSACTIONS

Vol. XXXIV, Parts I and II

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

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1. EDUCATION.

SYMPOSIUM ON "THE STATUS OF THE ENGINEER"

Vol. xxxiv—1915, pp. 293-332

Addresses by Messrs. L. B. Stillwell, E. W. Rice Jr., E. M. Herr, Alexander C. Humphreys, George F. Swain, Henry G. Stott and J. J. Carty.

2. GENERAL THEORY

COMPARISON OF CALCULATED AND MEASURED CORONA LOSS CURVES

F. W. Peek, Jr. **Vol. xxxiv—1915, pp. 269-276**

Corona loss curves made by various investigators on experimental and practical lines are compared with others calculated by the quadratic law with same conditions as to spacing, diameter, altitude, etc. The variations of theoretical and practical curves are accounted for and losses below visual critical voltage considered.

Discussion, pages 277-278, by Messrs. J. B. Whitehead, Philip Torchio and F. W. Peek, Jr.

General remarks on variation between theoretical and practical results. Difficulty of obtaining readings under practical conditions.

DISTORTION OF ALTERNATING-CURRENT WAVE CAUSED BY CYCLIC VARIATION IN RESISTANCE

Frederick Bedell and E. C. Mayer **Vol. xxxiv—1915, pp. 333-342**

Theoretical consideration of the distortion of current wave through creation of third harmonics caused by cyclic variation in resistance. Construction and comparison of curves, involving temperature lead and lag, positive and negative temperature coefficients, etc.

Discussion, pages 343-348, by Messrs. Clayton H. Sharp, C. Field-Frank, L. W. Chubb, Charles R. Underhill, M. G. Lloyd and Frederick Bedell.

General remarks on theory and on actual conditions occurring in an incandescent lamp circuit.

THE FLOW OF ENERGY

Robert A. Philip **Vol. xxxiv—1915, pp. 779-808**

Description of a new graphical method of representing the flow of energy showing the functions of generators, motors, transformers, transmission lines, and other parts of an electric distributing system in terms of the flow of energy through them.

No discussion.

THE ELECTRIC STRENGTH OF AIR—VI

J. B. Whitehead **Vol. xxxiv—1915, pp. 1035-1057**

Some of the simpler fundamental experiments on the electrical conductivity of air are described. The theory of ionization in gases is outlined and Townsend's proof that the law of corona forming intensity is in accord with the theory of ionization by collision is explained.

Discussion, pages 1058-1066, by Messrs. P.H. Thomas, J. B. Whitehead, F. W. Peek, Jr., E. E. F. Creighton, H. J. Ryan and L. W. Chubb.

Discussion of corona formation under various conditions and limitations.

THE RELUCTANCE OF SOME IRREGULAR MAGNETIC FIELDS

John F. H. Douglas **Vol. xxxiv—1915, pp. 1067-1125**

Mathematical and experimental methods of determining magnetic reluctance are discussed. The electric field of the electric generator is analyzed. The reluctance of various other magnetic fields is determined by experiment and mathematical computation. All results are put into charts and formulas for convenient use. The flux lines of transformers and induction motors are shown and the solution of the sine-wave alternator given.

Discussion, pages 1126-1134, by Messrs. C. R. Underhill, F. W. Peek, Jr., C. A. Adams, J. D. Ball, P. M. Lincoln, P. H. Thomas, L. W. Chubb and F. W. Carter.

A discussion of various magnetic fields encountered in machine design including the solenoid field and the dielectric field.

FORM FACTOR AND ITS SIGNIFICANCE—I

Frederick Bedell, assisted by
R. Bown and H. A. Pidgeon **Vol. xxxiv—1915, pp. 1135-1142**

Significance of form factor in the study of transformer losses. Every wave shape has a definite form factor, but the converse is not true. Form factor, therefore, is shown to have no general significance as an indicator of wave form or distortion. A general expression for form factor is derived.

Discussion, incorporated with that of paper by F. M. Mizushi on "An Analytical and Graphical Solution for Non-Sinusoidal Alternating Currents".

DISTORTION FACTORS—II

Frederick Bedell, assisted by
R. Bown and C. L. Swisher **Vol. xxxiv—1915, pp. 1143-1157**

The significance and usefulness of deviation, peak factor, harmonic factor, curve factor and differential and integral distortion factor. A possible factor combining the differential and integral factors is suggested. Variation of the different factors with phase, amplitude and frequency is given.

Discussion incorporated with that of paper by F. M. Mizushi on "An Analytical and Graphical Solution for Non-Sinusoidal Alternating Currents".

AN ANALYTICAL AND GRAPHICAL SOLUTION FOR NON-SINUSOIDAL ALTERNATING-CURRENTS

F. M. Mizushi **Vol. xxxiv—1915, pp. 1159-1170**

The solution for sinusoidal currents, series circuits, may be modified by the introduction of current distortion factors to hold for non-sinusoidal currents. The usual solution for parallel circuits may likewise be modified by similar voltage distortion factors. The general analytical solution for both cases is followed by the graphical solution and by special cases.

Discussion (including that of papers by F. Bedell, R. Bown, H. A. Pidgeon, and C. L. Swisher, and Report of Joint Committee on Inductive Interference), pages 1171-1200, by Messrs. C. A. Adams, L. W. Chubb, H. S. Osborne, W. V. Lyon, W. I. Middleton, C. L. Dawes, E. E. F. Creighton, J. B. Whitehead, W. J. Foster and F. Bedell.

Discussion of the effect of frequency on telephone operation with recommendations leading to the reduction of distortion of wave form in power circuits. A description of the pure wave generator.

THE PHASE ANGLE OF CURRENT TRANSFORMERS

C. L. Dawes **Vol. xxxiv—1915, pp. 1585-1598**

The determination of the phase angle of current transformers by means of a wattmeter and the corrections which must be applied to readings to correct unavoidable errors. Results of tests are given and the use of the a-c. potentiometer as a check method is described.

Discussion incorporated with that of paper by Charles Fortescue on "The Calibration of Current Transformers by Means of Mutual Inductance."

THE CALIBRATION OF CURRENT TRANSFORMERS BY MEANS OF MUTUAL INDUCTANCE

The Measurement of Mutual Inductance and Self-Inductance and Alternating-Current Resistance

Charles Fortescue **Vol. xxxiv—1915, pp. 1599-1615**

A statement of the reasons for the selection of mutual inductances as a means for calibrating current transformers and a description of the design and manufacture of the apparatus. Formula used in calculating mutual inductances and its limitation is given as well as methods of calibrating mutual inductances and of measuring rates and phase-displacements. An artificial method of loading transformers under test is proposed.

Discussion (including that of paper by C. L. Dawes), pages 1616-1626, by Messrs. G. A. Campbell, L. W. Chubb, C. H. Sharp, J. R. Craighead, C. W. Bates and C. L. Dawes.

A detailed discussion of general points involved in the paper with elaboration of certain points.

AN INVESTIGATION OF DIELECTRIC LOSSES WITH THE CATHODE RAY TUBE

John P. Minton **Vol. xxxiv—1915, pp. 1627-1677**

This paper discusses the theory of the cathode ray tube wattmeter and shows how it can be used to determine directly the power factors of insulations. The development of the cathode ray tube and its auxiliary apparatus is discussed. Measurements of dielectric losses, power factors and currents for varnished cloth and oil-treated pressboards are given, curves plotted and the empirical equations derived from them stated. The large and harmful effects of moisture and high temperature are clearly shown.

Discussion, pages 1678-1691, by Messrs. H. W. Fisher, R. W. Atkinson, F. W. Peek, Jr., C. L. Fortescue, W. C. Arsem, H. J. Ryan, R. P. Jackson,

C. L. Dawes, W. I. Middleton, C. H. Sharp, C. W. Davis and J. P. Minton.

A general discussion of points involved in the paper and a comparison of losses in gas, liquid and solid insulations.

THE EFFECT OF TRANSIENT VOLTAGES ON DIELECTRICS

F. W. Peek, Jr. **Vol. xxxiv—1915, pp. 1857-1909**

An investigation of the various phenomena affecting the strength of dielectrics and means of protecting them from transient voltages. An impulse generator from which voltages of any wave front, length of tail, etc., can be obtained is described. The strength of air between spheres and needles is given as well as time and voltage required for rupture. Transient spark-over and corona voltages for wires, surface spark-over, effects of polarity, air density, practical application, etc., are given. Transient spark-over voltage and time are recorded for oil and various solid dielectrics.

Discussion, pages 1910-1920, by Messrs. J. C. Clark, E. E. F. Creighton, P. H. Thomas, F. W. Peek, Jr., R. W. Sorensen, F. F. Brand, J. M. Weed and H. C. Stephens.

A general discussion with particular emphasis on spark lag, wet and dry spark-over and ionization.

EXPERIMENTAL RESEARCHES ON SKIN EFFECT IN CONDUCTORS

A. E. Kennelly, F. W. Laws and P. H. Pierce **Vol. xxxiv—1915, pp. 1953-2018**

The results of about one hundred series of tests, each covering a range in frequency up to about 5000 cycles per second, on the impedance of long loops of parallel conductors of different metals, sizes and cross-sectional forms. The measuring apparatus is described. The theory of skin effect in solid rods and in indefinitely wide flat strips is appended.

Discussion, pages 2019-2021, by Messrs. H. B. Dwight, J. E. Clem and L. P. Ferris.

A general discussion with particular reference to skin effect of conductors located within a-c. machinery.

HARMONICS IN TRANSFORMER MAGNETIZING CURRENTS

J. F. Peters **Vol. xxxiv—1915, pp. 2157-2173**

The cause and effects of higher harmonic currents in magnetizing currents of transformers are shown and a hypothetical case is analyzed. The effects with common schemes of connecting transformers are also entered into. The reason why third harmonics are not developed in "core-type" transformers connected star-star.

Discussion, pages 2174-2182, by Messrs. D. I. Cone, L. P. Ferris, N. S. Diamant and J. F. Peters.

Discussion of certain special cases and factors.

PHENOMENA ACCOMPANYING TRANSMISSION WITH SOME TYPES OF STAR TRANSFORMER CONNECTIONS

L. N. Robinson **Vol. xxxiv—1915, pp. 2183-2191**

This paper points out and explains some even harmonic phenomena attending the operation of star-star connected banks of transformers having grounded neutral on the line side only.

Discussion, pages 2192-2195, by Messrs. H. J. Ryan, H. Stephenson, W. A. Hillebrand, J. P. Jollyman, F. F. Brand and L. N. Robinson.

Remarks for and against the use of grounded neutral and tertiary delta.

ABNORMAL VOLTAGES IN TRANSFORMERS

J. Murray Weed **Vol. xxxiv—1915, pp. 2197-2232**

The paper deals with the electrical behavior of transformer windings when subjected to steep wave fronts and high-frequency wave trains. The dependance of the internal voltages produced, upon the distribution of capacity with the inductance of the winding, is discussed. An analysis is made of the facts and fundamental principles involved which will enable us to insulate for and guard against excessive internal voltages in a more scientific manner.

Discussion, pages 2233-2236, by Messrs. R. W. Sorensen, F. F. Brand P. H. Thomas and J. M. Weed.

A general discussion of methods of eliminating abnormal voltages in distribution systems.

CALCULATION OF SUDDEN SHORT-CIRCUIT PHENOMENA OF ALTERNATORS

N. S. Diamant **Vol. xxxiv—1915, pp. 2237-2273**

The theory and explanation of the electromagnetic phenomena involved in the sudden short circuit of alternators, as given by Berg and Boucherot, is briefly considered. New methods are developed for the experimental determination of these quantities. Also new methods are given, based on theoretical equations, for the calculation of short circuits directly from oscillographic records.

Data relating to the short circuit of a 45-kv-a. alternator are given; also an electrical device, designed by the writer for short circuiting a machine at any given point of the e. m. f. wave.

Discussion, pages 2274-2278, by Messrs. F. D. Newbury, C. J. Fechheimer and N. S. Diamant.

A general discussion of theoretical determinations vs. actual tests of short-circuit phenomena.

THE REPULSION START INDUCTION MOTOR

James L. Hamilton **Vol. xxxiv—1915, pp. 2443-2474**

This paper sets forth the general characteristics of the repulsion start induction motor and compares them with similar characteristics of d-c. motors and other a-c. motors. It outlines a definite and commercially practicable method of studying the electrical design of existing motors and of predetermining the design of new or proposed motors.

Discussion, pages 2475-2482, by Messrs. H. Weichsel, C. A. Weber, F. J. Bullivant, M. Brooks and J. L. Hamilton.

A general discussion of the design methods given by the author.

SINGLE-PHASE SQUIRREL-CAGE MOTOR WITH LARGE STARTING TORQUE AND PHASE CONPENSATION

Val A. Fynn **Vol. xxxiv—1915, pp. 2483-2508**

A description of a new single-phase motor which develops a large starting torque and operates with unity power factor. It outlines the manner in which the machine was developed, discusses the theory of its operation as well as novel points in its design and gives a number of test results obtained with motors of different sizes.

Discussion, page 2509, by Mr. H. Weichsel.

A brief description of the working characteristics of the motor.

THE CALCULATION OF THE LONG DISTANCE TRANSMISSION LINE UNDER CONSTANT ALTERNATING VOLTAGE

G. R. Dean **Vol. xxxiv—1915, pp. 2511-2532**

A mathematical dissertation on the real and imaginary quantities involved in the general solution of the differential equations which express the relations existing between current and voltage at any point of a transmission line. Special cases and numerical examples are worked out in detail.

No discussion.

DECOMPOSING MAGNETIC FIELDS INTO THEIR HIGHER HARMONICS

H. Weichsel **Vol. xxxiv—1915, pp. 2721-2738**

A description of methods of decomposing a magnetic field into its higher harmonics by representing the field shapes as geometrical figures composed of a number of triangular waves with certain phase displacements against each other. This avoids in many cases the usual long mathematical operations. Equations are deduced for the harmonics of various wave shapes based upon Fourier's equation for a triangular field.

Discussion, pages 2739-2745, by Messrs. G. R. Dean, J. L. Hamilton, N. S. Diamant, L. W. Chubb and H. Weichsel.

A general discussion of the methods employed by the author in decomposing magnetic fields.

3. UNITS, MEASUREMENTS AND INSTRUMENTS

ELECTRICAL PORCELAIN

I. Testing with a High Frequency Oscillator. II. The Problematical Points of Manufacture. III. Experiences and Experimental Investigations

E. E. F. Creighton **Vol. xxxiv—1915, pp. 465-552**

Part 1 treats of the reasons for using the high-frequency oscillator, its great value in the detection of flaws, punctures, etc. A description of the apparatus is given. Part 2 shows the principal factors in the manufacture of porcelain which affect the final product and are all important in obtaining a good electrical porcelain. Part 3 contains data on high-frequency tests. Methods of examining and determining the homogeneity of porcelain.

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Advantages and disadvantages of various methods. Performance data of insulators on lines of various voltages.

FORM FACTOR AND ITS SIGNIFICANCE—I

Frederick Bedell, assisted by
R. Bown and H. A. Pidgeon **Vol. xxxiv—1915, pp. 1135-1142**

Significance of form factor in the study of transformer losses. Every wave shape has a definite form factor, but the converse is not true. Form factor, therefore, is shown to have no general significance as an indicator of wave form or distortion. A general expression for form factor is derived.

Discussion incorporated with that of paper by F. M. Mizushi on "An Analytical and Graphical Solution for Non-Sinusoidal Alternating Currents".

THE PHASE ANGLE OF CURRENT TRANSFORMERS

C. L. Dawes **Vol. xxxiv—1915, pp. 1585-1598**

The determination of the phase angle of current transformers by means of a wattmeter and the corrections which must be applied to readings to correct unavoidable errors. Results of tests are given and the use of the a-c. potentiometer as a check method is described.

Discussion incorporated with that of paper by Charles Fortescue on "The Calibration of Current Transformers by Means of Mutual Inductance."

THE CALIBRATION OF CURRENT TRANSFORMERS BY MEANS OF MUTUAL INDUCTANCE

The Measurement of Mutual Inductance and Self-Inductance and Alternating Current Resistance

Charles Fortescue **Vol. xxxiv—1915, pp. 1599-1615**

A statement of the reasons for the selection of mutual inductances as a means for calibrating current transformers and a description of the design and manufacture of the apparatus. Formula used in calculating mutual inductances and its limitation is given as well as methods of calibrating mutual inductances and of measuring rates and phase-displacements. An artificial method of loading transformers under test is proposed.

Discussion (including that of paper by C. L. Dawes), pages 1616-1626, by Messrs. G. A. Campbell, L. W. Chubb, C. H. Sharp, J. R. Craighead, C. W. Bates and C. L. Dawes.

A detailed discussion of general points involved in the paper with elaboration of certain points.

AN INVESTIGATION OF DIELECTRIC LOSSES WITH THE CATHODE RAY TUBE

John P. Minton **Vol. xxxiv—1915, pp. 1627-1677**

This paper discusses the theory of the cathode ray tube wattmeter and shows how it can be used to determine directly the power factors of insulations. The development of the cathode ray tube and its auxiliary apparatus is discussed. Measurements of dielectric losses, power factors and currents for varnished cloth and oil-treated pressboards are given, curves plotted and the empirical equations derived from them stated. The large and harmful effects of moisture and high temperature are clearly shown.

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A general discussion of points involved in the paper and a comparison of losses in gas, liquid and solid insulations.

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F. W. Peek, Jr. **Vol. xxxiv—1915, pp. 1857-1909**

An investigation of the various phenomena affecting the strength of dielectrics and means of protecting them from transient voltages. An impulse generator from which voltages of any wave front, length of tail, etc., can be obtained is described. The strength of air between spheres and needles is given as well as time and voltage required for rupture. Transient spark-over and corona voltages for wires, surface spark-over, effects of polarity, air density, practical application, etc., are given. Transient spark-over voltage and time are recorded for oil and various solid dielectrics.

Discussion, pages 1910-1920, by Messrs. J. C. Clark, E. E. F. Creighton, P. H. Thomas, F. W. Peek, Jr., R. W. Sorensen, F. F. Brand, J. M. Weed and H. C. Stephens.

A general discussion with particular emphasis on spark lag, wet and dry spark-over and ionization.

EXPERIMENTAL RESEARCHES ON SKIN EFFECT IN CONDUCTORS

A. E. Kennelly, F. W. Laws and P. H. Pierce **Vol. xxxiv—1915, pp. 1953-2018**

The results of about one hundred series of tests, each covering a range in frequency up to about 5000 cycles per second, on the impedance of long loops of parallel conductors of different metals, sizes and cross-sectional forms. The measuring apparatus is described. The theory of skin effect in solid rods and in indefinitely wide flat strips is appended.

Discussion, pages 2019-2021, by Messrs. H. B. Dwight, J. E. Clem and L. P. Ferris.

A general discussion with particular reference to skin effect of conductors located within a-c. machinery.

CALCULATION OF SUDDEN SHORT-CIRCUIT PHENOMENA OF ALTERNATORS

N. S. Diamant **Vol. xxxiv—1915, pp. 2237-2273**

The theory and explanation of the electromagnetic phenomena involved in the sudden short circuit of alternators, as given by Berg and Boucherot, is briefly considered. New methods are developed for the experimental determination of these quantities. Also new methods are given, based on theoretical equations, for the calculation of short circuits directly from oscillographic records.

Data relating to the short circuit of a 45-kv-a. alternator are given; also an electrical device, designed by the writer for short circuiting a machine at any given point of the e. m. f. wave.

Discussion, pages 2274-2278, by Messrs. F. D. Newbury, C. J. Fechheimer and N. S. Diamant.

A general discussion of theoretical determinations vs. actual tests of short-circuit phenomena.

RATES AND RATE MAKING

Paul M. Lincoln **Vol. xxxiv—1915, pp. 2279-2318**

The necessity of recognizing load factor in rate schedules is emphasized. To obtain load factor necessitates the measurement of maximum demand; a new maximum demand meter is described which depends upon heat and heat storage. The theory of such meters is discussed. A new method of measuring power factor and volt-amperes is disclosed and a method of recognizing power factor in the rate for electric service is discussed.

Discussion, pages 2319-2360, by Messrs. W. McClellan, E. J. Cheney, P. Betts, J. W. Lieb, H. G. Stott, C. I. Hall, J. B. Taylor, H. W. Peck, H. Goodwin, Jr., W. N. Polakov, T. Jones, A.W. Burke, F. T. Leilich, R. S. Hale, E. J. Blake, A. Dow, J. G. De Remer, F. A. Sager, E. P. Roberts, R. A. Philip, H. L. Wallau, R. A. Lundquist, J. D. Mortimer, L. R. Lee, and P. M. Lincoln.

A general discussion for and against various methods of rate making.

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THE MAGNETIC PROPERTIES OF SOME IRON ALLOYS

Trygve D. Yensen **Vol. xxxiv—1915, pp. 2601-2641**

A description of experiments on various alloys of electrolytic iron melted in vacuo with other elements. The author deals briefly with the iron-boron and iron-carbon alloys, and presents results obtained with the iron-cobalt alloy. The iron-silicon alloy is treated in greater detail and most remarkable results are given.

Discussion, pages 2642-2670, by Messrs. T. Spooner, W. J. Wooldridge, J. D. Ball, M. Brooks, M. G. Lloyd, L. T. Robinson, N. W. Storer, C. W. Burrows, R. L. Sanford and T. D. Yensen.

A discussion of general conditions surrounding the testing of iron alloys and of results obtained by the author and other investigators.

THE EFFECT OF DISPLACED MAGNETIC PULSATIONS ON THE HYSTERESIS LOSS OF SHEET STEEL

L. W. Chubb and Thomas Spooner **Vol. xxxiv—1915, pp. 2671-2692**

A study of the constant varying reluctance to which the teeth of revolving electrical apparatus is subjected and the resultant displaced hysteresis loops. It is pointed out that the data from these displaced hysteresis loops limit the applicability of the Steinmetz formula to symmetrical loops. Recent tests and apparatus used, are described.

Discussion incorporated with that of paper by John D. Ball on "The Unsymmetrical Hysteresis Loop".

THE UNSYMMETRICAL HYSTERESIS LOOP

John D. Ball **Vol. xxxiv—1915, pp. 2693-2715**

Results and analyses of tests to determine losses in hysteresis loops wherein the magnetism is carried through cycles in which limiting values of flux are different in amount or the mean values of flux differ from zero. Such variations of magnetism occur in inductor generators, in teeth of induction machines, and in materials magnetized from rectifier circuits.

Discussion (including that of paper by L. W. Chubb and Thomas Spooner), pages 2716-2720, by Messrs. M. G. Lloyd, T. D. Yensen, T. Spooner and J. D. Ball.

A discussion of various methods of measurement and results obtained in each.

EXPERIMENTAL DATA CONCERNING THE SAFE OPERATING TEMPERATURE FOR MICA ARMATURE COIL INSULATION

F. D. Newbury **Vol. xxxiv—1915, pp. 2747-2764**

The results of three series of tests made on the first 3750-kv-a. generator installed at Niagara Falls, to determine internal copper temperatures. The object of the tests was to obtain data to assist in the determination of the safe maximum temperature of built-up mica-and-cambric (or mica-and-paper) insulation. The operating history of the generator is given. Tests show that when suitable mica insulation is used 150 deg. is a conservative limit.

Discussion, pages 2765-2780, by Messrs. P. Torchio, W. J. Foster, B. A. Behrend, H. P. Wood, C. F. Scott, H. F. Erben, C. E. Skinner, J. B. Fisken, P. M. Lincoln, F. W. Peek, T. E. Fowler, W. L. Waters, E. W. Stevenson and F. D. Newbury.

A discussion of the various factors to be considered in the establishment of a standard limiting temperature for insulation.

4. INSULATION AND DIELECTRIC PHENOMENA

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F. W. Peek, Jr. **Vol. xxxiv—1915, pp. 269-276**

Corona loss curves made by various investigators on experimental and practical lines are compared with others calculated by the quadratic law with same conditions as to spacing, diameter altitude, etc. The variations of theoretical and practical curves are accounted for and losses below visual critical voltage considered.

Discussion, pages 277-278, by Messrs. J. B. Whitehead, Philip Torchio and F. W. Peek, Jr.

General remarks on variation between theoretical and practical results. Difficulty of obtaining readings under practical conditions.

ELECTRICAL PRECIPITATION

F. G Cottrell **Vol. xxxiv—1915, pp. 387-396**

Historical sketch.

Discussion, incorporated with that of papers by W. W. Strong A. F. Nesbit and Linn Bradley.

ELECTRICAL PRECIPITATION

Theory of the Removal of Suspended Matter from Fluids

W. W. Strong **Vol. xxxiv—1915, pp. 397-404**

Method of calculating the amount of energy to remove suspended matter from fluids and relative efficiencies of various methods. The manner of distribution of energy of corona discharge and nature of ionization discussed. The application of the theory and the limits of usefulness.

Discussion incorporated with that of papers by Messrs. F. G. Cottrell, A. F. Nesbit and Linn Bradley.

THE THEORETICAL AND EXPERIMENTAL CONSIDERATION OF ELECTRICAL PRECIPITATION

A. F. Nesbit **Vol. xxxiv—1915, pp. 405-420**

Theory of electrical precipitation of suspended matter in gases is inseparably connected with the phenomena of ionization and laws of electrically charged bodies. Demonstration of precipitation in nature and the action of ionization, gravitation and the electric field. Data showing the superiority of negative corona and relative effectiveness of size and shape of electrodes, temperature and conductance of gases, polarity and uniformity of corona.

Discussion incorporated with that of papers of Messrs. F. G. Cottrell, W. W. Strong and Linn Bradley.

PRACTICAL APPLICATIONS OF ELECTRICAL PRECIPITATION AND PROGRESS OF THE RESEARCH CORPORATION

Linn Bradley **Vol. xxxiv—1915, pp. 421-457**

Technical and financial progress made by the Research Corporation since its organization with detailed description of several installations including data on voltages, electrode spacings, power consumption, etc. Mention is made of improvements in apparatus, the tendency toward standardization, and the field opening up for application. A selected bibliography is included.

Discussion (including that of papers by F. G. Cottrell, W. W. Strong and A. F. Nesbit), pages 458-464, by Messrs. W. S. Franklin Linn Bradley, Saul Dushman, Halbert P. Hill, A. F. Nesbit, L. W. Chubb, John B. Taylor, J. H. Davis, W. W. Strong and S. M. Kintner.

Criticisms and approvals of various methods and additional data on certain operations.

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Advantages and disadvantages of various methods. Performance data of insulators on lines of various voltages.

CONTINUOUS WAVES IN LONG DISTANCE RADIO TELEGRAPHY

L. F. Fuller **Vol. xxxiv—1915, pp. 809-827**

The theoretical transmission equations for both continuous and damped waves are considered with the empirical formulas for the latter. Ability to predetermine the probable normal daylight-sending radius of high-powered radio stations. Experiments with continuous waves between

San Francisco and Honolulu and the empirical formula derived. Curves for both day and night conditions are shown. Effects of changes of wave lengths upon transmission efficiency are discussed.

Discussion, pages 828-841, by Messrs. Alfred N. Goldsmith, J. Zenneck Lee de Forest, A. J. Hepburn, E. F. W. Alexanderson, G. H. Clark and L. F. Fuller.

Alternators for radio frequencies. The use of the arc as a generator. Discussion of "sunrise effect", interference, audibility and divergence factors.

THE ELECTRIC STRENGTH OF AIR—VI

J. B. Whitehead **Vol. xxxiv—1915, pp. 1035-1057**

Some of the simpler fundamental experiments on the electrical conductivity of air are described. The theory of ionization in gases is outlined and Townsend's proof that the law of corona forming intensity is in accord with the theory of ionization by collision is explained.

Discussion, pages 1058-1066, by Messrs. P. H. Thomas, J. B. Whitehead F. W. Peek, Jr., E. E. F. Creighton, H. J. Ryan and L. W. Chubb.

Discussion of corona formation under various conditions and limitations.

THE RELUCTANCE OF SOME IRREGULAR MAGNETIC FIELDS

John F. H. Douglass **Vol. xxxiv—1915, pp. 1067-1125**

Mathematical and experimental methods of determining magnetic reluctance are discussed. The electric field of the electric generator is analyzed. The reluctance of various other magnetic fields is determined by experiment and mathematical computation. All results are put into charts and formulas for convenient use. The flux lines of transformers and induction motors are shown and the solution of the sine-wave alternators given.

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FOUR YEARS OPERATING EXPERIENCE ON A HIGH-TENSION TRANSMISSION LINE

A. Bang **Vol. xxxiv—1915, pp. 1243-1263**

A careful record of all operating events of the high-tension transmission line of the Pennsylvania Water and Power Company's hydroelectric plant at Holtwood, Pa. Certain observations made on lightning flashovers, deterioration of insulators, sleet on cables, and various means adopted to prevent disturbances to operation from these causes.

Discussion (including that of papers by J. A. Walls, J. B. Leeper, W. E. Mitchell, P. M. Downing, F. C. Connery), pages 1264-1273, by Messrs. R. J. McClelland, A. S. McAllister, E. E. F. Creighton, E. A. Lof, L. C. Nicholson, J. B. Leeper and R. Bennett.

A general discussion of tower design, causes of failure, deterioration and failure of insulators.

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ARC PHENOMENA

A. G. Collis **Vol. xxxiv—1915, pp. 1921-1940**

A study of the arc phenomena accompanying the rupture of circuits in oil switches and description of a number of experiments made to determine the influence of differently shaped arcing contacts upon the disturbances following rupture of an a-c. circuit. The use of reactors is also considered.

Discussion, pages 1941-1951, by Messrs. E. B. Merriam, C. Lichtenberg, F. W. Harris and W. D. Peaslee.

A comparison of the experiences of others with those of the author.

DISCUSSION ON "REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE"

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The factors involved in inductive interference and methods of limiting or counteracting them with special reference to high frequency, reduction of harmonics and forms of line construction and transformer installation.

OVERHEAD ELECTROLYSIS AND PORCELAIN STRAIN INSULATORS

S. L. Foster **Vol. xxxiv—1915, pp. 2127-2136**

A description of the leakage of current from trolley wires to earth through insulated supports on all electrical overhead construction and the effect of this leakage on power and guy wires. The proper design of insulators to prevent this leakage. Electrolytic action caused by use of dissimilar metals, sulphuric acid and other fumes. A description of troubles, causes and cures in the San Francisco section.

Discussion, pages 2137-2140, by Messrs. L. W. Webb, L. Addicks, S. L. Foster, J. B. Fisken, J. H. Finney, T. M. Stateler and Paul L. Ost.

A general discussion of overhead electrolysis.

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A discussion of the various factors to be considered in the establishment of a standard limiting temperature for insulation.

5. ELECTRIC CONDUCTORS

THEORETICAL INVESTIGATION OF ELECTRIC TRANSMISSION SYSTEMS UNDER SHORT CIRCUIT CONDITIONS

I. W. Gross **Vol. xxxiv—1915, pp. 23-67**

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Discussion, pages 68-84, by Messrs. Henry G. Scott, Philip Torchio, Cassius M. Davis, H. R. Woodrow, James Lyman, John B. Taylor, R. W. Atkinson, Charles L. Fortescue, Hans Lippelt, S. I. Oesterreicher, Alfred E. Waller and I. W. Gross.

General discussion of the mechanical forces created by short-circuit conditions and the resisting forces in cables. The grouping of reactors.

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L. E. Imlay **Vol xxxiv—1915, pp. 233-240**

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Discussion, pages 241-245, by Messrs. Charles W. Davis, H. W. Fisher, W. S. Clark, J. P. Wintringham, C. A. Adams, W. S. Franklin, P. W. Sothman and George N. Lemmon.

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DISTORTION OF ALTERNATING-CURRENT WAVE CAUSED BY CYCLIC VARIATION IN RESISTANCE

Frederick Bedell and E. C. Mayer **Vol. xxxiv—1915, pp. 333-342**

Theoretical consideration of the distortion of current wave through creation of third harmonics caused by cyclic variation in resistance. Construction and comparison of curves, involving temperature lead and lag, positive and negative temperature co-efficients, etc.

Discussion, pages 343 348, by Messrs. Clayton H. Sharp, C. Field-Frank, L. W. Chubb, Charles R. Underhill, M. G. Lloyd and Frederick Bedell.

General remarks on theory and on actual conditions occurring in an incandescent lamp circuit.

PHYSICAL LIMITATIONS IN D-C. COMMUTATING MACHINERY

B. G. Lamme **Vol. xxxiv—1915, pp. 1739-1794**

The theory of commutation is considered only in its relation to the e. m. f's. generated in the coils short circuited by the brush; the limiting e. m. f's. per commutator bar and per brush are shown to be fixed principally by brush contact resistance. Flashing, burning of commutators, high mica, picking up of copper, noise vibration and flickering of voltage are taken up with their various inter-relations. A brief chapter is given on design limitations and an appendix covering a method for determining maximum capacity of d-c. machines in terms of the short circuit volts per commutator bar.

Discussion, pages 1795-1800, by Messrs. E. H. Martindale, H. R. Summerhayes, Gano Dunn and F. D. Newbury.

An enlargement of certain details of the paper with special emphasis on contact drop.

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6. MAGNETIC PROPERTIES AND TESTING OF IRON

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John F. H. Douglas **Vol. xxxiv—1915, pp. 1067-1125**

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THE EFFECT OF DISPLACED MAGNETIC PULSATIONS ON THE HYSTERESIS LOSS OF SHEET STEEL

L. W. Chubb and Thomas Spooner **Vol. xxxiv—1915, p. 2671-2692**

A study of the constant varying reluctance to which the teeth of revolving electrical apparatus is subjected and the resultant displaced hysteresis loops. It is pointed out that the data from these displaced hysteresis loops limit the applicability of the Steinmetz formula to symmetrical loops. Recent tests and apparatus used, are described.

Discussion incorporated with that of paper by John D. Ball on "The Unsymmetrical Hysteresis Loop."

THE UNSYMMETRICAL HYSTERSIS LOOP

John D. Ball **Vol. xxxiv—1915, pp. 2693-2715**

Results and analyses of tests to determine losses in hysteresis loops wherein the magnetism is carried through cycles in which limiting values of flux are different in amount or the mean values of flux differ from zero. Such variations of magnetism incur in inductor generators, in teeth of induction machines, and in materials magnetized from rectifier circuits.

Discussion (including that of paper by L. W. Chubb and Thomas Spooner), pages 2716-2720, by Messrs. M. G. Lloyd, T. D. Yensen, T. Spooner and J. D. Ball.

A discussion of various methods of measurement and results obtained in each.

DECOMPOSING MAGNETIC FIELDS INTO THEIR HIGHER HARMONICS

H. Weichsel **Vol. xxxiv—1915, pp. 2721-2738**

A description of methods of decomposing a magnetic field into its higher harmonics by representing the field shapes as geometrical figures composed of a number of triangular waves with certain phase displacements against the other. This avoids in many cases the usual long mathematical operations. Equations are deduced for the harmonics of various wave shapes based upon Fourier's equation for a triangular field.

Discussion, pages 2739-2745, by Messrs. G. R. Dean, J. L. Hamilton, N. S. Diamant, L. W. Chubb and H. Weichsel.

A general discussion of the methods employed by the author in decomposing magnetic fields.

8. TRANSFORMERS

A 100,000-VOLT PORTABLE SUBSTATION

Charles I. Burkholder and Nicholas Stahl **Vol. xxxiv—1915, pp. 279-290**

Detailed description of 4000-kv-a. capacity, easily portable substation, self-contained on a single car with dimensions to meet railroad clearances. The entire equipment designed for simplicity and dispatch in disassembly for transit and in reassembly. Unusual flexibility of voltage connections.

Discussion, pages 291-292, by Messrs. K. C. Randall, Julian C. Smith, L. W. Chubb and Nicholas Stahl.

Discussion of minor details.

THE PHASE ANGLE OF CURRENT TRANSFORMERS

C. L. Dawes **Vol. xxxiv—1915, pp. 1585-1598**

The determination of the phase angle of current transformers by means of a wattmeter and the corrections which must be applied to readings to correct unavoidable errors. Results of tests are given and the use of the a-c. potentiometer as a check method is described.

Discussion incorporated with that of paper by Charles Fortescue on "The Calibration of Current Transformers by Means of Mutual Inductance."

THE CALIBRATION OF CURRENT TRANSFORMERS BY MEANS OF MUTUAL INDUCTANCE

The Measurement of Mutual Inductance and Self-Inductance and Alternating-Current Resistance

Charles Fortescue **Vol. xxxiv—1915, pp. 1599-1615**

A statement of the reasons for the selection of mutual inductances as a means for calibrating current transformers and a description of the design and manufacture of the apparatus. Formula used in calculating mutual inductances and its limitation is given, as well as methods of calibrating mutual inductances and of measuring rates and phase-displacements. An artificial method of loading transformers under test is proposed.

Discussion (including that of paper by C. L. Dawes), pages 1616-1626, by Messrs. G. A. Campbell, L. W. Chubb, C. H. Sharp, J. R. Craighead, C. W. Bates and C. L. Dawes.

A detailed discussion of general points involved in the paper with elaboration of certain points.

DELTA-CROSS CONNECTIONS OF TRANSFORMERS FOR PARALLEL OPERATION OF TWO- AND THREE-PHASE SYSTEMS

George P. Roux **Vol. xxxiv—1915, pp. 2141-2152**

Two methods of transformer connections; the tee-cross and delta-cross, are described with their application for parallel operation of 2- and 3-phase systems, and an explanation given of voltage, current and phase relation, and the dephasing action which takes place in each case.

Discussion, pages 2153-2155, by Messrs. E. E. F. Creighton, W. A. Hillebrand, L. F. Blume and G. P. Roux

General discussion.

HARMONICS IN TRANSFORMER MAGNETIZING CURRENTS

J. F. Peters **Vol. xxxiv—1915, pp. 2157-2173**

The cause and effects of higher harmonic currents in magnetizing currents of transformers are shown and a hypothetical case is analyzed. The effects with common schemes of connecting transformers are also entered into. The reason why third harmonics are not developed in "core-type" transformers connected star star.

Discussion, pages 2174-2182, by Messrs. D. I. Cone, L. P. Ferris, N. S. Diamant and J. F. Peters.

Discussion of certain special cases and factors.

PHENOMENA ACCOMPANYING TRANSMISSION WITH SOME TYPES OF STAR TRANSFORMER CONNECTIONS

L. N. Robinson **Vol. xxxiv—1915, pp. 2183-2191**

This paper points out and explains some even harmonic phenomena attending the operation of star-star connected banks of transformers having grounded neutral on the line side only.

Discussion, pages 2192-2195, by Messrs. H. J. Ryan, H. Stephenson, W. A. Hillebrand, J. P. Jollyman, F. F. Brand and L. N. Robinson.

Remarks for and against the use of grounded neutral and tertiary delta.

ABNORMAL VOLTAGES IN TRANSFORMERS

J. Murray Weed **Vol. xxxiv—1915, pp. 2197-2232**

The paper deals with the electrical behavior of transformer windings when subjected to steep wave fronts and high-frequency wave trains. The dependance of the internal voltages produced, upon the distribution of capacity with the inductance of the winding, is discussed. An analysis is made of the facts and fundamental principles involved which will enable us to insulate for and guard against excessive internal voltages in a more scientific manner.

Discussion, pages 2233-2236, by Messrs. R. W. Sorensen, F. F. Brand, P. H. Thomas and J. M. Weed.

A general discussion of methods of eliminating abnormal voltages in distribution systems.

9. ELECTRICAL MACHINERY AND APPARATUS

THE CHARACTERISTICS OF ELECTRIC MOTORS INVOLVED IN THEIR APPLICATION

D. B. Rushmore **Vol xxxiv—1915, pp. 169-175**

A description of the growth of motor applications and an outline of the characteristics and limitations of motors involved in proper selection and application.

Discussion, pages 176-232, by Messrs. A. C. Lanier, Albert Brunt, K. A. Pauly, E. F. W. Alexanderson, C. J. Fechheimer, F. B. Crosby, A. E. Averrett, Lee F. Adams and C. A. Adams.

"The Direct-Current Motor in Industrial Applications", "Characteristics of Direct-Current Motors for Elevator Service", "Application of Flywheels to Motors", "A-C. Commutator Motors", "Synchronous Motors and Their Characteristics in Connection with Their Application", "Speed Regulation", "Induction Motor Characteristic Curves", "Bearings", "Motor Characteristics".

OIL CIRCUIT BREAKERS

Notes on Arc Phenomena and Tendencies in Design

K. C. Randall **Vol. xxxiv—1915, pp. 247-259**

A brief explanation of some of the arc phenomena in oil circuit breakers and description of present tendencies in oil breaker construction and practise. A proposed method for rating and specifying breakers.

Discussion, pages 260-268, by Messrs. W. S. Franklin, Philip Torchio, H. R. Summerhayes, P. M. Lincoln, E. B. Merriam, C. Lichtenberg, F. W. Harris and K. C. Randall.

General consideration of the factors involved in construction of successful breakers.

A 100,000-VOLT PORTABLE SUBSTATION

Charles I. Burkholder and Nicholas Stahl **Vol. xxxiv—1915, pp. 279-290**

Detailed description of 4000-kv-a. capacity, easily portable substation, self-contained on a single car with dimensions to meet railroad clearances. The entire equipment designed for simplicity and dispatch in disassembly for transit and in reassembly. Unusual flexibility of voltage connections.

Discussion, pages 291-292, by Messrs. K. C. Randall, Julian C. Smith, L. W. Chubb and Nicholas Stahl.

Discussion of minor details.

DIMMERS FOR TUNGSTEN LAMPS

Alfred E. Waller **Vol. xxxiv—1915 pp. 349-356**

Consideration of new factors involved in dimmer design through the development of the tungsten lamp with its positive temperature coefficient. Comparison of curves obtained with carbon and tungsten filaments. Commercial requirements.

Discussion, pages 357-361, by Messrs. Leonard Kebler, Charles D. Knight, John B. Taylor, Comfort A. Adams, W. S. Franklin, H. Ward Leonard and Alfred E. Waller.

Design details.

SEARCHLIGHTS

C. S. McDowell **Vol. xxxiv—1915, pp. 363-376**

Statement of the great necessity of an improved searchlight with outline constituent parts and desirable features. Method of testing mirrors, with figures. Comparison of Navy standard lamps and Beck 44-in. lamp.

Discussion, pages 377-385, by Messrs. R. B. Chillas, Jr., Karl Georg Frank, H. A. Hornor, W. S. Franklin and Clayton H. Sharp.

Design details and carbon statistics.

APPLICATION OF ELECTRICITY TO THE ORE HANDLING INDUSTRY

C. D. Gilpin **Vol. xxxiv—1915, pp. 619-637**

The typical method of handling ore from mine to blast furnace, describing machinery used in the different steps. The principles of application of motors to the various machines ahd the types best adapted to the work are discussed with the essential points of a power installation.

Discussion, pages 638-642, by Messrs. D. B. Rushmore, D. M. Petty, R. H. McLain, H. D. James, H. F. Stratton, R. R. Selleck and J. C. Lincoln.

Amplification of details.

LINE DISTURBANCE CAUSED BY SPECIAL SQUIRREL CAGE AND WOUND-ROTOR MOTORS WHEN STARTING ELEVATORS AND HOISTS

J. C. Lincoln **Vol. xxxiv—1915, pp. 643-653**

The author examines the cause of line disturbances in starting hoists and elevator motors and compares the performance of wound-rotor and squirrel-cage motors. Diagrams show graphically the current required for each type of motor to produce a given torque. Methods of control for different types also considered.

Discussion, pages 654-657, by Messrs. H. D. James, H. L. Wallau, R. H. McLain and J. C. Lincoln.

Certain motor characteristics as related to selection of proper size and type.

SOME TROUBLES ENCOUNTERED IN THE OPERATION OF CARBON BRUSHES IN DIRECT-CURRENT GENERATORS AND MOTORS

E. H. Martindale **Vol. xxxiv—1915, pp. 659-670**

A brief consideration of troubles which affect the operation of carbon brushes grouped under the following divisions; field, armature, commutator including brush rigging, external electrical and external mechanical.

Discussion, pages 671-679, by Messrs. D. B. Rushmore, H. R. Edgecomb, R. H. McLain, D. M. Petty, W. C. Kalb, J. H. Lapp, L. P. Crecelius, John P. Mallett, A. M. MacCutcheon and E. H. Martindale.

Certain details emphasized and amplification of others.

FRACTIONAL HORSE POWER MOTOR LOAD

Bernard Lester **Vol. xxxiv—1915, pp. 681-691**

An outline of the increasing use of fractional horse power motors and the chief causes for this advance as seen in the perfection of a reliable single-phase motor. A description of the design, construction, and operating characteristics of the commoner types of single-phase motors illustrated by the use of speed-torque curves. The correct application of small motors is emphasized. The author deals particularly with the split-phase induction motor and the functions of the centrifugal clutch.

Discussion, pages 692-694, by Mr. G. H. Garcelon.

A consideration of the selection of the motor for the best all-around service.

THE FACTORS INVOLVED IN MOTOR APPLICATIONS

David B. Rushmore **Vol. xxxiv—1915, pp. 695-697**

A summary of some of the factors involved in motor application.

Discussion, pages 698-778, by Messrs. A. P. Lewis, C. W. Larson, C. A. Austrom, W. Baum, H. H. Clark, F. A. Allner, Harold Goodwin, Jr., C. R. Weiss, A. M. Dudley, A. E. Averett, H. L. Wallau, C. Fair, R. W. Davis, H. R. Johnson, W. C. Yates, R. F. Schuchardt, Eric A. Lof, G. H. Jones, N. Currie, Jr., S. D. Sprong and R. M. Wilson.

A series of discussions on the following subjects: Motor Applications in the Rubber Industry; Friction Drive; Motor Installations from Safety and Insurance Viewpoints; Explosion-Proof Apparatus; The Influence of Inflammable Mine Gas upon the Design of Motors; Limitations as to Capacity and Type of Motor which May be Used on a System from the Central Station Standpoint; Factors Involved in Motor Applications; Link-Belt Silent Chain; The Selection of Motors from the Point of View of Frequency, Voltage and Phase, etc.; Individual Versus Group Drive; Safety First in Motor Applications; Load Conditions Affecting the Selection of Motors; Refrigerating Machinery; Alternating vs. Direct Current from the Standpoint of the Central Station.

INDUSTRIAL CONTROL IN THE FOUNDRY

R. H. McLain **Vol. xxxiv—1915, pp. 843-853**

A description of foundry control devices and the unusual degree of precaution necessary to keep out dirt. Enclosed cages, safety devices and special crane control. The difference between a-c. and d-c. control.

Discussion, pages 854-866, by Messrs. H. S. Newlin, T. E. Tynes, Max Hartenheim, Brent Wiley, James Farrington, S. C. Coey, Francis J. Burd, C. W. Bartlett, D. B. Rushmore, J. S. O'Donovan, Palmer Collins, C. D. Gilpin and R. H. McLain.

Amplification of points embodied in paper.

MILL CONTROLLERS

H. F. Stratton **Vol. xxxiv—1915, pp. 867-882**

An investigation of the acceleration of motors used in mill service. Important factors influencing the selection of proper gear ratio. Equations are deduced for determining theoretical limitations of speed and acceleration.

Discussion incorporated with that of paper by J. S. Riggs on "Steel Mill Controllers from the Operator's Standpoint."

STEEL MILL CONTROLLERS FROM THE OPERATORS' STANDPOINT

J. S. Riggs **Vol. xxxiv—1915, pp. 883-890**

The writer shows that no provision for emergencies can be allowed in blooming mill and rolling mill machinery and that it must always stand up to service, be as simple and as nearly fool-proof as possible. Advocates full-magnetic control. Requirements of different classes of machinery tabulated. Expense of duplication reduced by standardization.

Discussion, pages 891-916, by Messrs. H. F. Stratton, A. G. Pierce, D. B. Rushmore, Glenn E. Stoltz, M. A. Whiting, J. A. Albrecht, E. J. Murphy, R. H. McLain, K. A. Pauly, J. S. O'Donovan, Jacob F. Motz, S. C. Coey, Paul Caldwell, T. E. Tynes, W. T. Snyder, H. D. James, Graham Bright, W. H. Markland, Palmer Collins and C. D. Gilpin.

General discussion of important points embodied in the paper.

CONTROL OF DIRECT-CURRENT HOISTS IN IRON AND STEEL MILLS

G. E. Stoltz and W. O. Lum **Vol. xxxiv—1915, pp. 917-923**

The control problem discussed is confined entirely to the skip hoist. The load on the hoist is analyzed and proper cycle of operations determined. The characteristics of the motor and controller are considered as a unit.

Discussion incorporated with that of paper by W. T. Snyder on "Direct-Current Control for Hoisting Equipment in Industrial Plants."

DIRECT-CURRENT CONTROL FOR HOISTING EQUIPMENT IN INDUSTRIAL PLANTS

W. T. Snyder **Vol. xxxiv—1915, pp. 925-940**

A consideration of the various factors which must be taken into account when selecting a controller for mill machinery. The three different types of control as applied to the skip hoist, the high-speed coal hoist and the slow-speed ash hoist, and the functions absolutely essential to the controller in each case.

Discussion, pages 941-959, by Messrs. H. D. James, W. C. Kennedy, E. H. Martindale, J. H. Albrecht, Paul Caldwell, R. A. Black, John D. Wright, T. E. Tynes, C. S. Dauler, J. A. Albrecht, Francis J. Burd, J. S. O'Donovan, P. M. Lincoln, M. A. Whiting, G. E. Stoltz and W. T. Snyder.

Discussion of contact arcing, series contactors, grids and bridge-motion control, etc.

ALTERNATING-CURRENT CONTROLLERS FOR STEEL MILLS

Arthur Simon **Vol. xxxiv—1915, pp. 961-981**

A consideration of the control problems offered by squirrel-cage and wound-rotor induction machines when applied to steel mill service. The various types of a-c. controllers in use are described and illustrated and the advantages and disadvantages of each type as well as its limiting capacities are discussed. A number of typical installations are described.

Discussion incorporated with that of paper by Raymond E. Brown on "The Alternating-Current Coal Hoist."

THE ALTERNATING-CURRENT COAL HOIST

Raymond E. Brown **Vol. xxxiv—1915, pp. 983-990**

A description of an a-c. coal hoist in which dynamic braking is employed. Brakes and clutches operated by compressed air. The limiting factors in coal hoist control are described with means of securing an accurate stop.

Discussion (including that of paper by A. Simon), pages 991-1010, by Messrs. R. E. Brown, M. A. Whiting, J. H. Albrecht, R. H. McLain, W. C. Kennedy, C. D. Knight, W. F. Detwiler, W. O. Oschmann, G. Bright, C. S. Lankton, W. T. Snyder, E. S. Zuck, G. E. Stoltz, W. O. Lum, J. D. Wright, C. D. Gilpin and A. Simon.

A general discussion of the problems involved with instances of installations that have met particular cases successfully.

FIELDS OF MOTOR APPLICATION

David B. Rushmore **Vol. xxxiv—1915, pp. 1275-1283**

An introduction to a discussion on subject of Fields of Motor Application. An industry is defined from an economic standpoint and list of principal industries is given. The investigation of an industry from the standpoint of electric motor application is covered.

Discussion incorporated with that of paper by H. E. Stafford on "Electricity in Grain Elevators."

ELECTRICITY IN GRAIN ELEVATORS

H. E. Stafford **Vol. xxxiv—1915, pp. 1285-1301**

The storage capacity of grain at the terminals of Port Arthur and Fort William, is shown, together with the rated h.p. capacity of prime movers and the power used by different machines. Details of various plants and equipments are given and a comparison of steam and electrically driven plants as regards convenience, maintenance, operation and cost.

Discussion (including that of paper by D. B. Rushmore), pages 1302-1348, by Messrs. H. D. James, W. M. Hoen, H. F. Boe, W. C. Yates, T. Z. Simpers, E. W. Pilgrim, L. L. Tatum, J. C. Lincoln, J. H. Davis, H. W. Rogers, C. A. Kelsey, W. L. Merrill, C. C. Batchelder and R. H. Rogers.

Discussion on "The Electric Elevator," "Individual Motor Drive as Used in the Oil Flotation Process," "Fractional Horse-Power Motor Application," "Printing Presses," "Motor Applications of the Brick Manufacturing Industry," "Electricity in the Rubber Industry," "Dredges and Excavating Machinery," "The Sugar Industry," "The Paper Mill Industry," "The Portland Cement Industry," "The Handling of Freight in Terminals."

CLASSIFICATION OF ALTERNATING-CURRENT MOTORS

Val A. Fynn **Vol. xxxiv—1915, pp. 1349-1390**

The component field theory is suggested as best suited to the classification of a-c. motors. Descriptive names are offered for 44 a-c. motors including the principal forms of single-phase, polyphase, commutator and commutatorless. These names are such as to positively identify each machine. The author also points out the fact that there is no justification whatever of the term "repulsion" in connection with a-c. motors.

Discussion incorporated with that of paper by F. Creedy on "The Classification of Electromagnetic Machinery".

CLASSIFICATION OF ELECTROMAGNETIC MACHINERY

F. Creedy **Vol. xxxiv—1915, pp. 1391-1415**

A classification of all dynamo electric machinery according to five sets of characteristics, as follows: type of field; method of disposal of secondary power; use of commutators; method of magnetization; method of connection.

Discussion (including that of paper by V. A. Fynn), pages 1416-1428, by Messrs. A. S. McAllister, H. M. Hobart, C. R. Underhill, C. A. Adams, V. A. Fynn, W. C. Korthals Altes and F. Creedy.

A general discussion of various methods of classification of electromagnetic machinery.

PROGRESS IN THE IRON AND STEEL INDUSTRY AND THE ELECTRIC FURNACE

Karl Georg Frank **Vol. xxxiv—1915, pp. 1731-1738**

The history and development of the electric furnace and a prophecy as to the future development.

No discussion.

PHYSICAL LIMITATIONS IN D-C. COMMUTATING MACHINERY

B. G. Lamme **Vol. xxxiv—1915, pp. 1739-1794**

The theory of commutation is considered only in its relation to the e. m. f's. generated in the coils short circuited by the brush; the limiting e. m. f's. per commutator bar and per brush are shown to be fixed principally by brush contact resistance. Flashing, burning of commutators, high mica, picking up of copper, noise, vibration and flickering of voltage are taken up with their various inter-relations. A brief chapter is given on design limitations and an appendix covering a method for determining maximum capacity of d-c. machines in terms of the short-circuit volts per commutator bar.

Discussion, pages 1795-1800, by Messrs. E. H. Martindale, H. R. Summerhayes, Gano Dunn and F. D. Newbury.

An enlargement of certain details of the paper with special emphasis on contact drop.

STANDARD MARINE ELECTRICAL INSTALLATIONS

H. A. Hornor **Vol. xxxiv—1915, pp. 1821-1854**

The requirements of merchant and naval installations are cited in brief. The rules of classification societies are reviewed and present practise fully discussed. Specific applications to a number of different types of ships, both merchant and naval. are given. The reasons for the application of electric propulsion to a battleship are briefly given.

Discussion, page 1855, by Messrs. S. H. Blake and J. H. Finney.

A short general discussion of details.

ARC PHENOMENA.

A. G. Collis **Vol. xxxiv—1915, pp. 1921-1940**

A study of the arc phenomena accompanying the rupture of circuits in oil switches and description of a number of experiments made to determine the influence of differently shaped arcing contacts upon the disturbances following rupture of an a-c. circuit. The use of reactors is also considered.

Discussion, pages 1941-1951, by Messrs. E. B. Merriam, C. Lichtenberg, F. W. Harris and W. D. Peaslee.

A comparison of the experiences of others with those of the author.

CALCULATION OF SUDDEN SHORT-CIRCUIT PHENOMENA OF ALTERNATORS

N. S. Diamant **Vol. xxxiv—1915, pp. 2237-2273**

The theory and explanation of the electromagnetic phenomena involved in the sudden short circuit of alternators, as given by Berg and Boucherot, is briefly considered. New methods are developed for the experimental determination of these quantities. Also new methods are given, based on theoretical equations, for the calculation of short circuits directly from oscillographic records.

Data relating to the short circuit of a 45-kv-a. alternator are given; also an electrical device, designed by the writer for short circuiting a machine at any given point of the e. m. f. wave.

Discussion, pages 2274-2278, by Messrs. F. D. Newbury, C. J. Fechheimer and N. S. Diamant.

A general discussion of theoretical determinations vs. actual test of short-circuit phenomena.

CONSTRUCTION ELEMENTS OF THE TALLULAH FALLS DEVELOPMENT

Charles G. Adsit and W. P. Hammond **Vol. xxxiv—1915, pp. 2389-2438**

A very complete description of the Tallulah Falls hydroelectric development, one of the highest head water power plants in the world. Unit costs of the various items of construction are given.

Discussion, pages 2439-2442, by Messrs. A. J. Porskievies, A. S. Loizeaux, C. G. Adsit, C. O. Lens, Mr. Biglow, G. A. Hoadley, H. Pender, R. B. Owens and L. Jorgensen.

A general discussion of the details and unit costs of construction.

THE REPULSION START INDUCTION MOTOR

James L. Hamilton **Vol. xxxiv—1915, pp. 2443-2474**

This paper sets forth the general characteristics of the repulsion start induction motor and compares them with similar characteristies of d-c. motors and other a-c. motors. It outlines a definite and commercially practicable method of studying the electrical design of existing motors and of predetermining the design of new or proposed motors.

Discussion, pages 2475-2482, by Messrs. H. Weichsel, C. A. Weber, F. J. Bullivant, M. Brooks and J. L. Hamilton.

A general discussion of the design methods given by the author.

SINGLE-PHASE SQUIRREL-CAGE MOTOR WITH LARGE STARTING TORQUE AND PHASE COMPENSATION

Val. A. Fynn **Vol. xxxiv—1915, pp. 2483-2508**

A description of a new single-phase motor which develops a large starting torque and operates with unity power factor. It outlines the manner in which the machine was developed, discusses the theory of its operation as well as novel points in its design and gives a number of test results obtained with motors of different sizes.

Discussion, page 2509, by Mr. H. Weichsel.

A brief description of the working characteristics of the motor.

EXPERIMENTAL DATA CONCERNING THE SAFE OPERATING TEMPERATURE FOR MICA ARMATURE COIL INSULATION

F. D. Newbury **Vol. xxxiv—1915, pp. 2747-2764**

The results of three series of tests made on the first 3750-kv-a. generator installed at Niagara Falls, to determine internal copper temperatures. The object of the tests was to obtain data to assist in the determination of the safe maximum temperature of built-up mica-and-cambric (or mica-and-paper) insulation. The operating history of the generator is given. Tests show that when suitable mica insulation is used 150 deg. is a conservative limit.

Discussion, pages 2765-2780, by Messrs. P. Torchio, W. J. Foster, B. A. Behrend, H. P. Wood, C. F. Scott, H. F. Erben, C. E. Skinner, J. B. Fisken, P. M. Lincoln, F. W. Peek, T. E. Fowler, W. L. Waters, E. W. Stevenson and F. D. Newbury.

A discussion of the various factors to be considered in the establishment of a standard limiting temperature for insulation.

THE PRINCIPLES AND SYSTEMS OF ELECTRIC MOTOR CONTROL

C. D. Knight **Vol. xxxiv—1915, pp. 2781-2792**

A description of several types of resistance and explanation of the various forms of magnetic control in vogue to-day for both d-c. and a-c. motors. The characteristics embodied in contactor or magnetic switch design.

Discussion, pages 2793-2806, by Messrs. B. Jones, E. J. Murphy, W. I. Slichter, F. B. Crocker, J. H. Albrecht, H. F. Stratton, M. D. Goodman, F. W. Gay and C. D. Knight.

A discussion for and against types of control advocated by the author and an appeal for greater care in selection of motors and controllers in building equipment.

11. CENTRAL STATIONS

THE COMBINED OPERATION OF STEAM AND HYDRAULIC POWER IN THE PENNSYLVANIA WATER AND POWER COMPANY SYSTEM

John Abbet Walls **Vol. xxxiv—1915, pp. 2361-2368**

The experience of a large hydroelectric development on an erratic river, in endeavoring to accomplish most effective combined steam and hydroelectric operation. A plea is made for drawing up power contracts to encourage effective combined operation of hydroelectric plant with customers' existing steam equipment.

Discussion incorporated with that of paper by J. F. Vaughan on "Supplemental Power for Hydroelectric Systems".

SUPPLEMENTAL POWER FOR HYDROELECTRIC SYSTEMS

J. F. Vaughan **Vol. xxxiv—1915, pp. 2369-2381**

An outline of the functions of a steam plant furnishing relay and supplemental power for a system whose normal source of power is water.

Diagrams illustrate in a hypothetical case the division of load between the hydraulic and supplemental sources of power.

The paper also discusses some general data obtained from a number of New England water power systems.

Discussion (including that of paper by J. A. Walls), pages 2382-2388, by Messrs. A. S. Loizeaux, Mr. Birkhinhine and J. F. Vaughan.

A general discussion of the limiting factors in water power development.

CONSTRUCTION ELEMENTS OF THE TALLULAH FALLS DEVELOPMENT
Charles G. Adsit and W. P. Hammond **Vol. xxxiv—1915, pp. 2389-2438**

A very complete description of the Tallulah Falls hydroelectric development, one of the highest head water power plants in the world. Unit costs of the various items of construction are given.

Discussion, pages 2439-2442, by Messrs. A. J. Porskievies, A. S. Loizeaux, C. G. Adsit, C. O. Lens, Mr. Biglow, G. A. Hoadley, H. Pender, R. B. Owens and L. Jorgensen.

A general discussion of the details and unit costs of construction.

12. PARALLEL OPERATION

DELTA-CROSS CONNECTIONS OF TRANSFORMERS FOR PARALLEL OPERATION OF TWO- AND THREE-PHASE SYSTEMS
George P. Roux **Vol. xxxiv—1915, pp. 2141-2152**

Two methods of transformer connections; the tee-cross and delta-cross, are described with their application for parallel operation of 2- and 3-phase systems, and an explanation given of voltage, current and phase relation, and the dephasing action which takes place in each case.

Discussion, pages 2153-2155, by Messrs. E. E. F. Creighton, W. A. Hillebrand, L. F. Blume and G. P. Roux.

General discussion.

13. TRANSMISSION LINES

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—I
J. A. Walls **Vol. xxxiv—1915, pp. 1201-1212**

Notes on investigation of types of foundations, digging holes for foundations, concreting foundations and erecting towers.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—II
J. B. Leeper **Vol. xxxiv—1915, pp. 1213-1219**

The importance of properly designed tower anchors so that maximum strength of tower may be obtained with most economical outlay. Instances of loss where this has been overlooked.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—III
W. E. Mitchell **Vol. xxxiv—1915, pp. 1221-1226**

The development of the type of all-steel tower footing used by the Alabama Power Company for their 110,000-volt transmission lines is outlined with a summary of conditions influencing the designs finally arrived at.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—IV

P. M. Downing **Vol. xxxiv—1915, pp. 1227-1231**

The weakest link of a transmission system is the line. Towers are strongly advocated for trunk lines and conditions to be met in design are given. The use of concrete footings is recommended.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—V

F. C. Connery **Vol. xxxiv—1915, pp. 1233-1241**

A brief explanation is presented of the types of towers, tower foundations, etc., along with details of field practise used in connection with two lines of towers carrying six 190,000-cir. mil, seven-strand copper conductors between Niagara Falls and Toronto. The question of dispensing with massive concrete foundations for towers is dealt with.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUR YEARS OPERATING EXPERIENCE ON A HIGH-TENSION TRANSMISSION LINE

A. Bang **Vol. xxxiv—1915, pp. 1243-1263**

A careful record of all operating events of the high-tension transmission line of the Pennsylvania Water and Power Company's hydroelectric plant at Holtwood, Pa. Certain observations made on lightning flashovers, deterioration of insulators, sleet on cables, and various means adopted to prevent disturbances to operation from these causes.

Discussion (including that of papers by J. A. Walls, J. B. Leeper, W. E. Mitchell, P. M. Downing, F. C. Connery), pages 1264-1273, by Messrs. R. J. McClelland, A. S. McAllister, E. E. F. Creighton, E. A. Lof, L. C. Nicholson, J. B. Leeper and R. Bennett.

A general discussion of tower design, causes of failure, deterioration and failure of insulators.

OVERHEAD ELECTROLYSIS AND PORCELAIN STRAIN INSULATORS

S. L. Foster **Vol. xxxiv—1915, pp. 2127-2136**

A description of the leakage of current from trolley wires to earth through insulated supports on all electrical overhead construction and the effect of this leakage on power and guy wires. The proper design of insulators to prevent this leakage. Electrolytic action caused by use of dissimilar metals, sulphuric acid and other fumes. A description of troubles, causes and cures in the San Francisco section.

Discussion, pages 2137-2140, by Messrs. L. W. Webb, L. Addicks, S. L. Foster, J. B. Fisken, J. H. Finney, T. M. Stateler and Paul L. Ost.

A general discussion of overhead electrolysis.

PHENOMENA ACCOMPANYING TRANSMISSION WITH SOME TYPES OF STAR TRANSFORMER CONNECTIONS

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This paper points out and explains some even harmonic phenomena attending the operation of star-star connected banks of transformers having grounded neutral on the line side only.

Discussion, pages 2192-2195, by Messrs. H. J. Ryan, H. Stephenson, W. A. Hillebrand, J. P. Jollyman, F. F. Brand and L. N. Robinson.

Remarks for and against the use of grounded neutral and tertiary delta.

THE CALCULATION OF THE LONG DISTANCE TRANSMISSION LINE UNDER CONSTANT ALTERNATING VOLTAGE

G. R. Dean **Vol. xxxiv—1915, pp. 2511-2532**

A mathematical dissertation on the real and imaginary quantities involved in the general solution of the differential equations which express the relations existing between current and voltage at any point of a transmission line. Special cases and numerical examples are worked out in detail.

No discussion.

14. ELECTRIC SERVICE DISTURBANCES AND PROTECTION.

THEORETICAL INVESTIGATION OF ELECTRIC TRANSMISSION SYSTEMS UNDER SHORT-CIRCUIT CONDITIONS

I. W. Gross **Vol. xxxiv—1915, pp. 23-67**

An investigation of the mechanical forces between busbars and the phases of three-conductor cables under short-circuit conditions. An analytical treatment of heating with typical curves. The effectiveness of reactors.

Discussion, pages 68-84, by Messrs. Henry G. Stott. Philip Torchio, Cassius M. Davis, H. R. Woodrow, James Lyman, John B. Taylor, R. W. Atkinson, Charles L. Fortescue, Hans Lippelt, S. I. Oesterreicher, Alfred E. Waller and I. W. Gross.

General discussion of the mechanical forces created by short-circuit conditions and the resisting forces in cables. The grouping of reactors.

EFFECT OF MOISTURE IN THE EARTH ON TEMPERATURE OF UNDERGROUND CABLES

L. E. Imlay **Vol. xxxiv—1915, pp. 233-240**

Descriptions of investigations of temperature of underground cables and methods suggested for elimination of hot spots and general lowering of temperature below danger point. Statistics and curves of seasonal variations in cable temperature.

Discussion, pages 241-245, by Messrs. Charles W. Davis, H. W. Fisher, W. S. Clark, J. P. Wintringham, C. A. Adams, W. S. Franklin, P. W. Sothman and George N. Lemmon.

Errors liable to occur in determining cable temperatures. European practise.

OIL CIRCUIT BREAKERS

Notes on Arc Phenomena and Tendencies in Design

K. C. Randall **Vol. xxxiv—1915, pp. 247-259**

A brief explanation of some of the arc phenomena in oil circuit breakers and description of present tendencies in oil breaker construction and practise. A proposed method for rating and specifying breakers.

Discussion, Pages 260-268, by Messrs. W. S. Franklin, Philip Torchio, H. R. Summerhayes, P. M. Lincoln, E. B. Merriam, C. Lichtenberg, F. W. Harris and K. C. Randall.

General consideration of the factors involved in construction of successful breakers.

COMPARISON OF CALCULATED AND MEASURED CORONA LOSS CURVES

F. W. Peek, Jr. **Vol. xxxiv—1915, pp. 269-276**

Corona loss curves made by various investigators on experimental and practical lines are compared with others calculated by the quadratic law with same conditions as to spacing, diameter, altitude, etc. The variations of theoretical and practical curves are accounted for and losses below visual critical voltage considered.

Discussion, pages 277-278, by Messrs. J. B. Whitehead, Philip Torchio and F. W. Peek, Jr.

General remarks on variation between theoretical and practical results. Difficulty of obtaining readings under practical conditions.

DISTORTION OF ALTERNATING-CURRENT WAVE CAUSED BY CYCLIC VARIATION IN RESISTANCE

Frederick Bedell and E. C. Mayer **Vol. xxxiv—1915, pp. 333-342**

Theoretical consideration of the distortion of current wave through creation of third harmonics caused by cyclic variation in resistance. Construction and comparison of curves, involving temperature lead and lag, positive and negative temperature coefficients, etc.

Discussion, pages 343-348, by Messrs. Clayton H. Sharp, C. Field-Frank, L. W. Chubb, Charles R. Underhill, M. G. Lloyd and Frederick Bedell.

General remarks on theory and on actual conditions occurring in an incandescent lamp circuit.

ELECTRICAL PORCELAIN

I. Testing with a High-Frequency Oscillator. II. The Problematical Points of Manufacture. III. Experiences and Experimental Investigation

E. E. F. Creighton **Vol. xxxiv—1915, pp. 465-552**

Part I treats of the reasons for using the high-frequency oscillator, its great value in the detection of flaws, punctures, etc. A description of the apparatus is given. Part II shows the principal factors in the manufacture of porcelain which affect the final product and are all important in obtaining a good electrical porcelain. Part III contains data on high-frequency tests. Methods of examining and determining the homogeneity of porcelain.

Discussion, pages 553-576, by Messrs. A. O. Austin, C. Field-Frank, J. T. Lawson, P. W. Sothman, F. Osgood, L. L. Israel, R. P. Jackson, W. H. Jacobi, J. C. Smith, H. J. Ryan and J. S. Lapp.

Advantages and disadvantages of various methods. Performance data of insulators on lines of various voltages.

LINE DISTURBANCE CAUSED BY SPECIAL SQUIRREL-CAGE AND WOUND-ROTOR MOTORS WHEN STARTING ELEVATORS AND HOISTS

J. C. Lincoln **Vol. xxxiv—1915, pp. 643-653**

The author examines the cause of line disturbances in starting hoists and elevator motors and compares the performance of wound-rotor and squirrel-cage motors. Diagrams show graphically the current required for each type of motor to produce a given torque. Methods of control for different types also considered.

Discussion, pages 654-657, by Messrs. H. D. James, H. L. Wallau, R. H. McLain and J. C. Lincoln.

Certain motor characteristics as related to selection of proper size and type.

THE FACTORS INVOLVED IN MOTOR APPLICATIONS

David B. Rushmore **Vol. xxxiv—1915, pp. 695-697**

A summary of some of the factors involved in motor application.

Discussion, pages 698-778, by Messrs. A. P. Lewis, C. W. Larson, C. A. Austrom, W. Baum, H. H. Clark, F. A. Allner, Harold Goodwin, Jr., C. R. Weiss, A. M. Dudley, A. E. Averrett, H. L. Wallau, C. Fair, R. W. Davis, H. R. Johnson, W. C. Yates, R. F. Schuchardt, Eric A. Lof, G. H. Jones, N. Currie, Jr., S. D. Sprong and R. M. Wilson.

A series of discussions on the following subjects: Motor Applications in the Rubber Industry; Friction Drive; Motor Installations from Safety and Insurance Viewpoints; Explosion-Proof Apparatus; The Influence of Inflammable Mine Gas upon the Design of Motors; Limitations as to Capacity and Type of Motor which may be Used on a System from the Central Station Standpoint; Factors Involved in Motor Applications; Link-Belt Silent Chain; The Selection of Motors from the Point of View of Frequency, Voltage and Phase, etc.; Individual Versus Group Drive; Safety First in Motor Applications; Load Conditions Affecting the Selection of Motors; Refrigerating Machinery; Alternating vs. Direct Current from the Standpoint of the Central Station.

DISTORTION FACTORS—II

Frederick Bedell, assisted by
R. Bown and C. L. Swisher **Vol. xxxiv—1915, pp. 1143-1157**

The significance and usefulness of deviation, peak factor, harmonic factor, curve factor and differential and integral distortion factor. A possible factor combining the differential and integral factors is suggested. Variation of the different factors with phase, amplitude and frequency is given.

Discussion incorporated with that of paper by F. M. Mizushi on "An Analytical and Graphical Solution for Non-Sinusoidal Alternating Currents."

FOUR YEARS OPERATING EXPERIENCE ON A HIGH-TENSION TRANSMISSION LINE

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A general discussion of tower design, causes of failure, deterioration and failure of insulators.

PHYSICAL LIMITATIONS IN D-C. COMMUTATING MACHINERY

B. G. Lamme **Vol. xxxiv—1915, pp. 1739-1794**

The theory of commutation is considered only in its relation to the e. m. f's. generated in the coils short circuited by the brush; the limiting e. m. f's. per commutator bar and per brush are shown to be fixed principally by brush contact resistance. Flashing, burning of commutators, high mica, picking up of copper, noise, vibration and flickering of voltage are taken up with their various inter-relations. A brief chapter is given on design limitations and an appendix covering a method for determining maximum capacity of d-c. machines in terms of the short-circuit volts per commutator bar.

Discussion, pages 1795-1800, by Messrs. E. H. Martindale, H. R. Summerhayes, Gano Dunn and F. D. Newbury.

An enlargement of certain details of the paper with special emphasis on contact drop.

THE EFFECT OF TRANSIENT VOLTAGES ON DIELECTRICS

F. W. Peek, Jr. **Vol. xxxiv—1915, pp. 1857-1909**

An investigation of the various phenomena affecting the strength of dielectrics and means of protecting them from transient voltages. An impulse generator from which voltages of any wave front, length of tail, etc., can be obtained is described. The strength of air between spheres and needles is given as well as time and voltage required for rupture. Transient spark-over and corona voltages for wires, surface spark-over, effects of polarity, air density, practical application, etc., are given. Transient spark-over voltage and time are recorded for oil and various solid dielectrics.

Discussion, pages 1910-1920, by Messrs. J. C. Clark, E. E. F. Creighton, P. H. Thomas, F. W. Peek, Jr., R. W. Sorensen, F. F. Brand, J. M. Weed and H. C. Stephens.

A general discussion with particular emphasis on spark lag, wet and dry spark-over and ionization.

ARC PHENOMENA

A. G. Collis **Vol. xxxiv—1915, pp. 1921-1940**

A study of the arc phenomena accompanying the rupture of circuits in oil switches and description of a number of experiments made to determine the influence of differently shaped arcing contacts upon the disturbances following rupture of an a-c. circuit. The use of reactors is also considered.

Discussion, pages 1941-1951, by Messrs. E. B. Merriam, C. Lichtenberg, F. W. Harris and W. D. Peaslee.

A comparison of the experiences of others with those of the author.

DISCUSSION ON "REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE"

Vo. xxxiv—1915, pp. 2113-2125

The factors involved in inductive interference and methods of limiting or counteracting them with special reference to high frequency, reduction of harmonics and forms of line construction and transformer installation.

OVERHEAD ELECTROLYSIS AND PORCELAIN STRAIN INSULATORS

S. L. Foster **Vol. xxxiv—1915, pp. 2127-2136**

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A general discussion of overhead electrolysis.

HARMONICS IN TRANSFORMER MAGNETIZING CURRENTS

J. F. Peters **Vol. xxxiv—1915, pp. 2157-2173**

The cause and effects of higher harmonic currents in magnetizing currents of transformers are shown and a hypothetical case is analyzed. The effects with common schemes of connecting transformers are also entered into. The reason why third harmonics are not developed in "core-type" transformers connected star-star.

Discussion, pages 2174-2182, by Messrs. D. I. Cone, L. P. Ferris, N. S. Diamant and J. F. Peters.

Discussion of certain special cases and factors.

PHENOMENA ACCOMPANYING TRANSMISSION WITH SOME TYPES OF STAR TRANSFORMER CONNECTIONS

L. N. Robinson **Vol. xxxiv—1915, pp. 2183-2191**

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Remarks for and against the use of grounded neutral and tertiary delta.

ABNORMAL VOLTAGES IN TRANSFORMERS

J. Murray Weed **Vol. xxxiv—1915, pp. 2197-2232**

The paper deals with the electrical behavior of transformer windings when subjected to steep wave fronts and high-frequency wave trains. The dependance of the internal voltages produced, upon the distribution of capacity with the inductance of the winding, is discussed. An analysis is made of the facts and fundamental principles involved which will enable us to insulate for and guard against excessive internal voltages in a more scientific manner.

Discussion, pages 2233-2236, by Messrs. R. W. Sorensen, F. F. Brand, P. H. Thomas and J. M. Weed.

A general discussion of methods of eliminating abnormal voltages in distribution systems.

CALCULATION OF SUDDEN SHORT-CIRCUIT PHENOMENA OF ALTERNATORS
N. S. Diamant **Vol. xxxiv—1915, pp. 2237-2273**

The theory and explanation of the electromagnetic phenomena involved in the sudden short circuit of alternators, as given by Berg and Boucherot, is briefly considered. New methods are developed for the experimental determination of these quantities. Also new methods are given, based on theoretical equations, for the calculation of short circuits directly from oscillographic records.

Data relating to the short circuit of a 45-kv-a. alternator are given; also an electrical device, designed by the writer for short circuiting a machine at any given point of the e. m. f. wave.

Discussion, pages 2274-2278, by Messrs. F. D. Newbury, C. J. Fechheimer and N. S. Diamant.

A general discussion of theoretical determination vs. actual tests of short-circuit phenomena.

16. CONTROL, REGULATION AND SWITCHING

OIL CIRCUIT BREAKERS

Notes on Arc Phenomena and Tendencies in Design
K. C. Randall **Vol. xxxiv—1915, pp. 247-259**

A brief explanation of some of the arc phenomena in oil circuit breakers and description of present tendencies in oil breaker construction and practise. A proposed method for rating and specifying breakers.

Discussion, pages 260-268, by Messrs. W. S. Franklin, Philip Torchio, H. R. Summerhayes, P. M. Lincoln, E. B. Merriam, C. Lichtenberg, F. W. Harris and K. C. Randall.

General consideration of the factors involved in construction of successful breakers.

A 100,000-VOLT PORTABLE SUBSTATION

Charles I. Burkholder and Nicholas Stahl **Vol. xxxiv—1915, pp. 279-290**

Detailed description of 4000-kv-a. capacity, easily portable substation, self-contained on a single car with dimensions to meet railroad clearances. The entire equipment designed for simplicity and dispatch in disassembly for transit and in reassembly. Unusual flexibility of voltage connections.

Discussion, pages 291-292, by Messrs. K. C. Randall, Julian C. Smith, L. W. Chubb and Nicholas Stahl.

Discussion of minor details.

DIMMERS FOR TUNGSTEN LAMPS

Alfred E. Waller **Vol. xxxiv—1915, pp. 349-356**

Consideration of new factors involved in dimmer design through the development of the tungsten lamp with its positive temperature coefficient. Comparison of curves obtained with carbon and tungsten filaments. Commercial requirements.

Discussion, pages 357-361, by Messrs. Leonard Kebler, Charles D. Knight, John B. Taylor, Comfort A. Adams, W. S. Franklin, H. Ward Leonard and Alfred E. Waller.

Design details.

INDUSTRIAL CONTROL IN THE FOUNDRY

R. H. McLain **Vol. xxxiv—1915, pp. 843-853**

A description of foundry control devices and the unusual degree of precaution necessary to keep out dirt. Enclosed cages, safety devices and special crane control. The difference between a-c. and d-c. control.

Discussion, pages 854-866, by Messrs. H. S. Newlin, T. E. Tynes, Max Hartenheim, Brent Wiley, James Farrington, S. C. Coey, Francis J. Burd, C. W. Bartlett, D. B. Rushmore, J. S. O'Donovan, Palmer Collins, C. D. Gilpin and R. H. McLain.

Amplification of points embodied in paper.

MILL CONTROLLERS

H. F. Stratton **Vol. xxxiv—1915, pp. 867-882**

An investigation of the acceleration of motors used in mill service. Important factors influencing the selection of proper gear ratio. Equations are deduced for determining theoretical limitations of speed and acceleration.

Discussion incorporated with that of paper by J. S. Riggs on "Steel Mill Controllers from the Operator's Standpoint".

STEEL MILL CONTROLLERS FROM THE OPERATORS STANDPOINT

J. S. Riggs **Vol. xxxiv—1915, pp. 883-890**

The writer shows that no provision for emergencies can be allowed in blooming mill and rolling mill machinery and that it must always stand up to service, be as simple and as nearly fool-proof as possible. Advocates full-magnetic control. Requirements of different classes of machinery tabulated. Expense of duplication reduced by standardization.

Discussion, pages 891-916, by Messrs. H. F. Stratton, A. G. Pierce, D. B. Rushmore, Glenn E. Stoltz, M. A. Whiting, J. A. Albrecht, E. J. Murphy, R. H. McLain, K. A. Pauly, J. S. O'Donovan, Jacob F. Motz, S. C. Coey, Paul Caldwell, T. E. Tynes, W. T. Snyder, H. D. James, Graham Bright, W. H. Markland, Palmer Collins and C. D. Gilpin.

General discussion of important points embodied in the paper.

CONTROL OF DIRECT-CURRENT HOISTS IN IRON AND STEEL MILLS

G. E. Stoltz and W. O. Lum **Vol. xxxiv—1915, pp. 917-923**

The control problem discussed is confined entirely to the skip hoist. The load on the hoist is analyzed and proper cycle of operations determined. The characteristics of the motor and controller are considered as a unit.

Discussion incorporated with that of paper by W. T. Snyder on "Direct-Current Control for Hoisting Equipment in Industrial Plants."

DIRECT-CURRENT CONTROL FOR HOISTING EQUIPMENT IN INDUSTRIAL PLANTS

W. T. Snyder **Vol. xxxiv—1915, pp. 925-940**

A consideration of the various factors which must be taken into account when selecting a controller for mill machinery. The three different types of control as applied to the skip hoist, the high-speed coal hoist and the slow-speed ash hoist, and the functions absolutely essential to the controller in each case.

Discussion, pages 941-959, by Messrs. H. D. James, W. C. Kennedy, E. H. Martindale, J. H. Albrecht, Paul Caldwell, R. A. Black, John D Wright, T. E. Tynes, C. S. Dauler, J. A. Albrecht, Francis J. Burd, J. S. O'Donovan, P. M. Lincoln, M. A. Whiting, G. E. Stoltz and W. T. Snyder.

Discussion of contact arcing, series contactors, grids and bridge-motion control, etc.

ALTERNATING-CURRENT CONTROLLERS FOR STEEL MILLS

Arthur Simon **Vol. xxxiv—1915, pp. 961-981**

A consideration of the control problems offered by squirrel-cage and wound-rotor induction machines when applied to steel mill service. The various types of a-c. controllers in use are described and illustrated and the advantage and disadvantage of each type as well as its limiting capacities are discussed. A number of typical installations are described.

Discussion incorporated with that of paper by Raymond E. Brown on "The Alternating-Current Coal Hoist."

THE ALTERNATING-CURRENT COAL HOIST

Raymond E. Brown **Vol. xxxiv—1915, pp. 983-990**

A description of an a-c. coal hoist in which dynamic braking is employed. Brakes and clutches operated by compressed air. The limiting factors in coal hoist control are described with means of securing an accurate stop.

Discussion (including that of paper by A. Simon), pages 991-1010, by Messrs. R. E. Brown, M. A. Whiting, J. H Albrecht, R. H. McLain, W. C. Kennedy, C. D. Knight, W. F. Detwiler, W. O. Oschmann, G. Bright, C. S. Lankton, W. T. Snyder, E. S. Zuck, G. E. Stoltz, W. O. Lum, J. D. Wright, C. D. Gilpin and A. Simon.

A general discussion of the problems involved with instances of installations that have met particular cases successfully.

AUTOMATICALLY CONTROLLED SUBSTATIONS

With Particular Reference to Their Application to Interurban Electric Railways

E. W. Allen and Edward Taylor **Vol. xxxiv—1915, pp. 1801-1815**

An analysis of the duties of the attendant of a substation and an appeal for the substitution of present day reliable automatic devices with consequent economy and improvement of service. The paper advocates a reduction in size and an increase in the number of stations. A description is given of the automatically controlled substations installed on the lines of the Elgin and Belvidere Electric Railway.

Discussion, pages 1816-1819, by Messrs. A. H. Babcock, R. F. Schuchardt, H. R. Summerhayes and C. W. Place.

A discussion of the variety of substations designed and economy possibilities.

ARC PHENOMENA

A. G. Collis **Vol. xxxiv—1915, pp. 1921-1940**

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Discussion, pages 1941-1951, by Messrs. E. B. Merriam, C. Lichtenberg, F. W. Harris and W. D. Peaslee.

A comparison of the experiences of others with those of the author.

DELTA-CROSS CONNECTIONS OF TRANSFORMERS FOR PARALLEL OPERATION OF TWO- AND THREE-PHASE SYSTEMS

George P. Roux **Vol. xxxiv—1915, pp. 2141-2152**

Two methods of transformer connections; the tee-cross and delta-cross are described with their application for parallel operation of 2- and 3-phase systems, and an explanation given of voltage, current and phase relation, and the dephasing action which takes place in each case.

Discussion, pages 2153-2155, by Messrs. E. E. F. Creighton, W. A. Hillebrand. L. F. Blume, G. P. Roux.

General discussion.

PHENOMENA ACCOMPANYING TRANSMISSION WITH SOME TYPES OF STAR TRANSFORMER CONNECTIONS

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Remarks for and against the use of grounded neutral and tertiary delta.

THE REPULSION START INDUCTION MOTOR

James L. Hamilton **Vol. xxxiv—1915, pp. 2443-2474**

This paper sets forth the general characteristics of the repulsion start induction motor and compares them with similar characteristics of d-c. motors and other a-c. motors. It outlines a definite and commercially practicable method of studying the electrical design of existing motors and of predetermining the design of new or proposed motors.

Discussion, pages 2475-2482, by Messrs. H. Weichsel, C. A. Weber, F. J. Bullivant, M. Brooks and J. L. Hamilton.

A general discussion of the design methods given by the author.

SINGLE-PHASE SQUIRREL-CAGE MOTOR WITH LARGE STARTING TORQUE AND PHASE COMPENSATION

Val A. Fynn **Vol. xxxiv—1915, pp. 2483-2508**

A description of a new single-phase motor which develops a large starting torque and operates with unity power factor. It outlines the manner in which the machine was developed, discusses the theory of its operation as well as novel points in its design and gives a number of test results obtained with motors of different sizes.

Discussion, page 2509, by Mr. H. Weichsel.

A brief description of the working characteristics of the motor.

THE PRINCIPLES AND SYSTEMS OF ELECTRIC MOTOR CONTROL

C. D. Knight **Vol. xxxiv—1915, pp. 2781-2792**

A description of several types of resistance and explanation of the various forms of magnetic control in vogue to-day for both d-c. and a-c.

motors. The characteristics embodied in contactor or magnetic switch design.

Discussion, pages 2793-2806, by Messrs. B. Jones, E. J. Murphy, W. I. Slichter, F. B. Crocker, J. H. Albrecht, H. F. Stratton, M. D. Goodman, F. W. Gay and C. D. Knight.

A discussion for and against types of control advocated by the author and an appeal for greater care in selection of motors and controllers in building equipment.

17. TRACTION

CONDITIONS AFFECTING THE SUCCESS OF MAIN LINE ELECTRIFICATION

W. S. Murray **Vol. xxxiv—1915, pp. 85-124**

Description of general conditions affecting the success of railroad electrification from both the public and railroad viewpoints. New Haven taken as particular example with tabulated statistics from monthly operating report. Statistics of construction costs of various catenary construction types.

Discussion, pages 125-144, by Messrs. Alfred W. Gibbs, George R. Henderson, E. H. McHenry, C. Renshaw, F. E. Wynne, Philip Torchio, W. A. Del Mar, R. H. Wheeler and W. S. Murray.

General discussion of electrification. Appeal for standardization of power systems. Consideration of outside power sources.

OVERHEAD CONTACT SYSTEMS, CONSTRUCTION AND COSTS—PART I

E. J. Amberg **Vol. xxxiv—1915, pp. 1459-1470**

A brief analysis of the systems and points to be considered in equipping trunk lines with overhead catenary construction, with special reference to the New Haven electrification. The paper is subdivided into five parts, *viz;* catenary systems, supporting structures, sectionalization, special construction and cost data.

Discussion incorporated with that of paper by Paul Lebenbaum on "The Contact System of the Southern Pacific Company, Portland Division".

CONSTRUCTION, MAINTENANCE AND COST OF OVERHEAD CONTACT SYSTEMS—PART II—CATENARY CONSTRUCTION

F. Zogbaum **Vol. xxxiv—1915, pp. 1471-1485**

A general review of the problems involved in the maintenance and cost of an overhead high-voltage system of the catenary type. The particular subject treated is the contact system and transmission lines of the New York, Westchester and Boston Railway.

Discussion incorporated with that of paper by Paul Lebenbaum on "The Contact System of the Southern Pacific Company, Portland Division".

CONTACT SYSTEM OF THE BUTTE, ANACONDA AND PACIFIC RAILWAY

J. B. Cox **Vol. xxxiv—1915, pp. 1487-1516**

A review of conditions that caused the selection of the overhead contact system and the adoption of the roller pantograph on the B. A. & P. R. R. Description of special hangers, pulloffs, etc. required. Explanation of relatively high cost of installation.

Discussion incorporated with that of paper by Paul Lebenbaum on "The Contact System of the Southern Pacific Company, Portland Division".

THIRD RAIL AND TROLLEY SYSTEM OF THE WEST JERSEY AND SEASHORE RAILROAD

J. V. B. Duer **Vol. xxxiv—1915, pp. 1517-1533**

The details and cost of construction of the contact system as originally installed and subsequently modified and extended. Operating experiences and cost of maintenance for seven consecutive years, track and third-rail resistances are given.

Discussion incorporated with that of paper by Paul Lebenbaum on "The Contact System of the Southern Pacific Company, Portland Division".

TOP-CONTACT UNPROTECTED CONDUCTOR RAIL FOR 600-VOLT TRACTION SYSTEMS

Charles H. Jones **Vol. xxxiv—1915, pp. 1535-1545**

The various factors to be considered in the design of a 600-volt contact rail system. The question of weight and quality of rail, insulating, supporting, bonding and jointing and control of contraction and expansion are covered in detail. Total cost and cost per mile for various conditions, given.

Discussion incorporated with that of paper by Paul Lebenbaum on "The Contact System of the Southern Pacific Company, Portland Division."

CONTACT CONDUCTORS AND COLLECTORS FOR ELECTRIC RAILWAYS

C. J. Hixson **Vol. xxxiv—1915, pp. 1547-1560**

A general classification of collecting devices according to the existing A. I. E. E. classification of contact conductors. Rail and wire systems are considered with their collectors. Many data are arranged in form of curves expressing the factors essential to proper collection.

Discussion incorporated with that of paper by Paul Lebenbaum on "The Contact System of the Southern Pacific Company, Portland Division."

THE CONTACT SYSTEM OF THE SOUTHERN PACIFIC COMPANY, PORTLAND DIVISION

Paul Lebenbaum **Vol. xxxiv—1915, pp. 1561-1574**

A detailed description of the 1550-volt overhead contact system of the electrified lines of the Southern Pacific Company, Portland Division. The design and materials of construction are given in detail and the cost per mile, of material and labor, are tabulated.

Discussion (including that of papers by E. J. Amberg, F. Zogbaum, J. B. Cox, J. V. B. Duer, C. H. Jones and C. J. Hixson), pages 1575-1584, by Messrs. L. D. Nordstrum, J. V. B. Duer, G. H. Hill, H. M. Hobart, A. S. McAllister, D. C. Jackson, R. L. Allen, F. Zogbaum, D. D. Ewing, J. B. Cox and C. J. Hixson.

General discussion of details involved in the trolley and third rail electrification problem.

AUTOMATICALLY CONTROLLED SUBSTATIONS

With Particular Reference to Their Application to Interurban Electric Railways

E. W. Allen and Edward Taylor **Vol. xxxiv—1915, pp. 1801-1815**

An analysis of the duties of the attendant of a substation and an appeal for the substitution of present day reliable automatic devices with consequent economy and improvement of service. The paper advocates a reduction in size and an increase in the number of stations. A description is given of the automatically controlled substations installed on the lines of the Elgin and Belvidere Electric Railway.

Discussion, pages 1816-1819, by Messrs. A. H. Babcock, R. F. Schuchardt, H. R. Summerhayes and C. W. Place.

A discussion of the variety of substations designed and economy possibilities.

18. LIGHTING AND LAMPS

DIMMERS FOR TUNGSTEN LAMPS

Alfred E. Waller **Vol. xxxiv—1915, pp. 349-356.**

Consideration of new factors involved in dimmer design through the development of the tungsten lamp with its positive temperature coefficient. Comparison of curves obtained with carbon and tungsten filaments. Commercial requirements.

Discussion, pages 357-361, by Messrs. Leonard Kebler, Charles D. Knight, John B. Taylor, Comfort A. Adams, W. S. Franklin, H. Ward Leonard and Alfred E. Waller.

Design details.

THE EFFECTIVE ILLUMINATION OF STREETS

Preston S. Millar **Vol. xxxiv—1915, pp. 1429-1448**

The effectiveness of street lighting with particular reference to silhouette effect, specular reflection and glare. A presentation of the variables upon which the effectiveness of street illumination depends. Illuminating efficiency values for several modern street illuminations are given. Statistics and photographs of some very recent installations.

Discussion, pages 1449-1458, by Messrs. G. H. Stickney, D. C. Jackson, H. L. Wallau, W. R. Moulton, H. H. Magdsick, W. H. Pratt, J. B. Whitehead, P. Junkersfeld, A. T. Baldwin, L. D. Nordstrum, C. E. Stephens and P. S. Millar.

General discussion of street illumination.

19. ELECTRICITY IN THE ARMY AND NAVY

SEARCHLIGHTS

C. S. McDowell **Vol. xxxiv—1915, pp. 363-376**

Statement of the great necessity of an improved searchlight with outline of constituent parts and desirable features. Method of testing mirrors, with figures. Comparison of Navy standard lamps and Beck 44-in. lamp.

Discussion, pages 377-385, by Messrs. R. B. Chillas, Jr., Karl Georg Frank, H. A. Hornor, W. S. Franklin and Clayton H. Sharp.

Design details and carbon statistics.

STANDARD MARINE ELECTRICAL INSTALLATIONS

H. A. Hornor **Vol. xxxiv—1915, pp. 1821-1854**

The requirements of merchant and naval installations are cited in brief. The rules of classification societies are reviewed and present practise fully discussed. Specific applications to a number of different types of ships, both merchant and naval, are given. The reasons for the application of electric propulsion to a battleship are briefly given.

Discussion, page 1855, by Messrs. S. H. Blake and J. H. Finney. A short general discussion of details.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

THE CHARACTERISTICS OF ELECTRIC MOTORS INVOLVED IN THEIR APPLICATION

D. B. Rushmore **Vol. xxxiv—1915, pp. 169-175**

A description of the growth of motor applications and an outline of the characteristics and limitations of motors involved in proper selection and application.

Discussion, pages 176-232, by Messrs. A. C. Lanier, Albert Brunt, K. A. Pauly, E. F. W. Alexanderson, C. J. Fechheimer, F. B. Crosby, A. E. Averrett, Lee F. Adams, C. A. Adams.

"The Direct-Current Motor in Industrial Applications," "Characteristics of Direct-Current Motors for Elevator Service," "Application of Flywheels to Motors," "A-C. Commutator Motors," "Synchronous Motors and Their Characteristics in Connection with Their Application," "Speed Regulation," "Induction Motor Characteristic Curves," "Bearings," "Motor Characteristics."

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Design details and carbon statistics.

ELECTRICAL PRECIPITATION

F. G. Cottrell **Vol. xxxiv—1915, pp. 387-396**

Historical sketch.

Discussion incorporated with that of papers by W. W. Strong, A. F. Nesbit and Linn Bradley.

ELECTRICAL PRECIPITATION

Theory of the Removal of Suspended Matter from Fluids

W. W. Strong **Vol. xxxiv—1915, pp. 397-404**

Method of calculating the amount of energy to remove suspended matter from fluids and relative efficiencies of various methods. The manner of distribution of energy of corona discharge and nature of ionization discussed. The application of the theory and the limits of usefulness.

Discussion incorporated with that of papers by Messrs. F. G. Cottrell, A. F. Nesbit and Linn Bradley.

THE THEORETICAL AND EXPERIMENTAL CONSIDERATION OF ELECTRICAL PRECIPITATION

A. F. Nesbit **Vol. xxxiv—1915, pp. 405-420**

Theory of electrical precipitation of suspended matter in gases is inseparably connected with the phenomena of ionization and laws of electrically charged bodies. Demonstration of precipitation in nature and the action of ionization, gravitation and the electric field. Data showing the superiority of negative corona and relative effectiveness of size and shape of electrodes, temperature and conductance of gases, polarity and uniformity of corona.

Discussion, incorporated with that of papers by Messrs. F. G. Cottrell, W. W. Strong and Linn Bradley.

PRACTICAL APPLICATIONS OF ELECTRICAL PRECIPITATION AND PROGRESS OF THE RESEARCH CORPORATION

Linn Bradley **Vol. xxxiv—1915, pp. 421-457**

Technical and financial progress made by the Research Corporation since its organization with detailed description of several installations including data on voltages, electrode spacings, power consumption, etc. Mention is made of improvements in apparatus, the tendency toward standardization and the field opening up for application. A selected bibliography is included.

Discussion, (including that of papers by F. G. Cottrell, W. W. Strong and A. F. Nesbit), pages 458-464, by Messrs. W. S. Franklin, Linn Bradley, Saul Dushman, Halbert P. Hill, A. F. Nesbit, L. W. Chubb, John B. Taylor, J. H. Davis, W. W. Strong and S. M. Kintner.

Criticisms and approvals of various methods and additional data on certain operations.

FIXATION OF ATMOSPHERIC NITROGEN

Leland L. Summers **Vol. xxxiv—1915, pp. 577-611**

Description of the very definite commercial limitations of nitrogen fixation set by the vast natural deposits of sodium nitrate with which the production of a substitute must compete. The very low efficiency of electrical fixation processes is emphasized and the possibilities of a combination electrical and chemical process discussed. Comparative figures are given showing the amount of energy necessary per kilogram of nitrogen fixed.

Discussion, pages 612-617, by Messrs. Joseph W. Richards, J. L. R. Hayden, D. B. Rushmore, Charles A. Doremus, F. V. Henshaw, Frank B. Washburn and Leland L. Summers.

Consideration of the power situation with relation to a fixation plant. The Rjukanfos, Norway plant.

APPLICATION OF ELECTRICITY TO THE ORE HANDLING INDUSTRY

C. D. Gilpin **Vol. xxxiv—1915, pp. 619-637**

The typical method of handling ore from mine to blast furnace, describing machinery used in the different steps. The principles of application of motors to the various machines and the types best adapted to the work are discussed with the essential points of a power installation.

Discussion, pages 638-642, by Messrs. D. B. Rushmore, D. M. Petty, R. H. McLain, H. D. James, H. F. Stratton, R. R. Selleck, J. C. Lincoln. Amplification of details.

THE FACTORS INVOLVED IN MOTOR APPLICATIONS

David B. Rushmore **Vol. xxxiv—1915, pp. 695-697**

A summary of some of the factors involved in motor application.

Discussion, pages 698-778, by Messrs. A. P. Lewis, C. W. Larson, C. A. Austrom, W. Baum, H. H. Clark, F. A. Allner, Harold Goodwin, Jr., C. R. Weiss, A. M. Dudley, A. E. Averrett, H. L. Wallau, C. Fair, R. W. Davis, H. R. Johnson, W. C. Yates, R. F. Schuchardt, Eric A. Lof, G. H. Jones, N. Currie, Jr., S. D. Sprong and R. M. Wilson.

A series of discussions on the following subjects: Motor Applications in the Rubber Industry; Friction Drive; Motor Installations from Safety and Insurance Viewpoints; Explosion-Proof Apparatus; The Influence of Inflammable Mine Gas upon the Design of Motors; Limitations as to Capacity and Type of Motor which may be Used on a System from the Central Station Standpoint; Factors Involved in Motor Applications; Link-Belt Silent Chain; The Selection of Motors from the Point of View of Frequency, Voltage and Phase, etc.; Individual Versus Group Drive; Safety First in Motor Applications; Load Conditions Affecting the Selection of Motors; Refrigerating Machinery; Alternating vs. Direct Current from the Standpoint of the Central Station.

FIELDS OF MOTOR APPLICATION

David B. Rushmore **Vol. xxxiv—1915, pp. 1275-1283**

An introduction to a discussion on subject of Fields of Motor Application. An industry is defined from an economic standpoint and list of principal industries is given. The investigation of an industry from the standpoint of electric motor application is covered.

Discussion incorporated with that of paper by H. E. Stafford on "Electricity in Grain Elevators."

ELECTRICITY IN GRAIN ELEVATORS

H. E. Stafford **Vol. xxxiv—1915, pp. 1285-1301**

The storage capacity of grain at the terminals of Port Arthur and Fort William, is shown, together with the rated h. p. capacity of prime movers and the power used by different machines. Details of various plants and equipments are given and a comparison of steam and electrically driven plants as regards covenience, maintenance, operation and cost.

Discussion (including that of papers by D. B. Rushmore), pages 1302-1348, by Messrs. H. D. James, W. M. Hoen, H. F. Boe, W. C. Yates, T. Z. Simpers, E. W. Pilgrim, L. L. Tatum, J. C. Lincoln, J. H. Davis, H. W. Rogers, C. A. Kelsey, W. L. Merrill, C. C. Batchelder and R. H. Rogers.

Discussion on "The Electric Elevator", "Individual Motor Drive as Used in the Oil Flotation Process", "Fractional Horse-Power Motor Application", "Printing Presses", "Motor Applications of the Brick Manufacturing Industry", "Electricity in the Rubber Industry", "Dredges and Excavating Machinery", "The Sugar Industry", "The Paper Mill Industry", "The Portland Cement Industry", "The Handling of Freight in Terminals."

STANDARD MARINE ELECTRICAL INSTALLATIONS

H. A. Hornor **Vol. xxxiv—1915, pp. 1821-1854**

The requirements of merchant and naval installations are cited in brief. The rules of classification societies are reviewed and present practise fully discussed. Specific applications to a number of different types of ships, both merchant and naval, are given. The reasons for the application of electric propulsion to a battleship are briefly given.

Discussion, page 1855, by Messrs. S. H. Blake and J. H. Finney.

A short general discussion of details.

21. TELEPHONY AND TELEGRAPHY

CONTINUOUS WAVES IN LONG DISTANCE RADIO TELEGRAPHY

L. F. Fuller **Vol. xxxiv—1915, pp. 809-827**

The theoretical transmission equations for both continuous and damped waves are considered with the empirical formulas for the latter. Ability to predetermine the probable normal daylight-sending radius of high-powered radio stations. Experiments with continuous waves between San Francisco and Honolulu and the empirical formula derived. Curves for both day and night conditions are shown. Effects of changes of wave lengths upon transmission efficiency are discussed.

Discussion, pages 828-841, by Messrs. Alfred N. Goldsmith, J. Zenneck, Lee de Forest, A. J. Hepburn, E. F. W. Alexanderson, G. H. Clark and L. F. Fuller.

Alternators for radio frequencies. The use of the arc as a generator. Discussion of "sunrise effect", interference, audibility and divergence factors.

HOW BELL INVENTED THE TELEPHONE

Thomas A. Watson **Vol. xxxiv—1915, pp. 1011-1021**

A historical sketch of the invention and development of the telephone.

AN ANALYTICAL AND GRAPHICAL SOLUTION FOR NON-SINUSOIDAL ALTERNATING CURRENTS

F. M. Mizushi **Vol. xxxiv—1915, pp. 1159-1170**

The solution for sinusoidal currents, series circuits, may be modified by the introduction of current distortion factors to hold for non-sinusoidal currents. The usual solution for parallel circuits may likewise be modified by similar voltage distortion factors. The general analytical solution for both cases is followed by the graphical solution and by special cases.

Discussion (including that of papers by F. Bedell, R. Bown, H. A. Pidgeon, and C. L. Swisher, and Report of Joint Committee on Inductive Interference), pages 1171-1200, by Messrs. C. A. Adams, L. W. Chubb, H. S. Osborne, W. V. Lyon, W. I. Middleton, C. L. Dawes, E. E. F. Creighton, J. B. Whitehead, W. J. Foster and F. Bedell.

Discussion on the effect of frequency on telephone operation with recommendations leading to the reduction of distortion of wave form in power circuits. A description of pure wave generator.

SUBMARINE CABLE RAPID TELEGRAPHY: OCEAN AND INTERCONTINENTAL TELEPHONY

Bela Gati **Vol. xxxiv—1915, pp. 2079-2107**

A description of methods and apparatus applicable for increasing the speed of cable telegraphy and ocean telephony. Various makes of relays, sensitive receivers, microphones and loaded circuits are considered in detail.

Discussion, pages 2108-2111, by Mr. O. B. Blackwell.

A general discussion on doubtful points of the paper.

DISCUSSION ON "REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE"

Vol. xxxiv—1915, pp. 2113-2125

The factors involved in inductive interference and methods of limiting or counteracting them with special reference to high frequency, reduction of harmonics and forms of line construction and transformer installation.

22. MISCELLANEOUS TOPICS AND INSTITUTE AFFAIRS

THE MULTIPLEX COST AND RATE SYSTEM

Otto B. Goldman **Vol. xxxvi—1915, pp. 1-17**

Method of determining the cost of electric service with variable demands The value of competition and the regulation of profits. Examples covering various conditions are worked out.

Discussion, pages 18-21, by Messrs. Julian Loebenstein, L. C. Tomlinson, and O. B. Goldman.

General discussion with particular attention to growth factor and the time-watt-hour meter.

THE BEST CONTROL OF PUBLIC UTILITIES

Frank G. Baum **Vol. xxxiv—1915, pp. 145-167**

An appeal for the establishment of class rates with an outline for the method of determining these rates. Examples are given to show why various class rates differ.

Discussion incorporated with that of paper by F. G. Baum on "Class Rates for Light and Power Systems or Territories".

SYMPOSIUM ON "THE STATUS OF THE ENGINEER"

Vol. xxxiv—1915, pp. 293-332

Addresses by Messrs. L. B. Stillwell, E. W. Rice, Jr., E. M. Herr, Alexander C. Humphreys, George F. Swain, Henry G. Stott and J. J. Carty.

FIXATION OF ATMOSPHERIC NITROGEN

Leland L. Summers **Vol. xxxiv—1915, pp. 577-611**

Description of the very definite commercial limitations of nitrogen fixation set by the vast natural deposits of sodium nitrate with which the production of a substitute must compete. The very low efficiency of electrical fixation processes is emphasized and the possibilities of a combination electrical and chemical process discussed. Comparative figures are given showing the amount of energy necessary per kilogram of nitrogen fixed.

Discussion, pages 612-617, by Messrs. Joseph W. Richards, J. L. R. Hayden, D. B. Rushmore, Charles A. Doremus, F. V. Henshaw, Frank B. Washburn, and Leland L. Summers.

Consideration of the power situation with relation to a fixation plant. The Rjukanfos, Norway plant.

THE FLOW OF ENERGY

Robert A. Philip **Vol. xxxiv—1915, pp. 779-808**

Description of a new graphical method of representing the flow of energy showing the functions of generators, motors, transformers, transmission lines, and other parts of an electric distributing system in terms of the flow of energy through them.

No discussion.

HOW BELL INVENTED THE TELEPHONE

Thomas A. Watson **Vol. xxxiv—1915, pp. 1011-1021**

A historical sketch of the invention and development of the telephone.

THE TREND OF ELECTRICAL DEVELOPMENT

President's Address

Paul M. Lincoln **Vol. xxxiv—1915, pp. 1023-1034**

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—I

J. A. Walls **Vol. xxxiv—1915, pp. 1201-1212**

Notes on investigation of types of foundations, digging holes for foundations, concreting foundations and erecting towers.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—II

J. B. Leeper **Vol. xxxiv—1915, pp. 1213-1219**

The importance of properly designed tower anchors so that maximum strength of tower may be obtained with most economical outlay. Instances of loss where this has been overlooked.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—III

W. E. Mitchell **Vol. xxxiv—1915, pp. 1221-1226**

The development of the type of all-steel tower footing used by the Alabama Power Company for their 110,000-volt transmission lines is outlined with a summary of conditions influencing the designs finally arrived at.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—IV

P. M. Downing **Vol. xxxiv—1915, pp. 1227-1231**

The weakest link of a transmission system is the line. Towers are strongly advocated for trunk lines and conditions to be met in design are given. The use of concrete footings is recommended.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION—V

F. C. Connery **Vol. xxxiv—1915, pp. 1233-1241**

A brief explanation is presented of the types of towers, tower foundations, etc. along with details of field practise used in connection with two lines of towers carrying six 190,000-cir. mil, seven-strand copper conductors between Niagara Falls and Toronto. The question of dispensing with massive concrete foundations for towers is dealt with.

Discussion incorporated with that of paper by A. Bang on "Four Years Operating Experience on a High-Tension Transmission Line."

CLASSIFICATION OF ALTERNATING-CURRENT MOTORS

Val A. Fynn **Vol. xxxiv—1915, pp. 1349-1390**

The component field theory is suggested as best suited to the classification of a-c. motors. Descriptive names are offered for 44 a-c. motors including the principal forms of single-phase, polyphase, commutator and commutatorless. These names are such as to positively identify each machine. The author also points out the fact that there is no justification whatever of the term "repulsion" in connection with a-c. motors.

Discussion incorporated with that of paper by F. Creedy on "The Classification of Electromagnetic Machinery."

THE CLASSIFICATION OF ELECTROMAGNETIC MACHINERY

F. Creedy **Vol. xxxiv—1915, pp. 1391-1415**

A classification of all dynamo electric machinery according to five sets of characteristics, as follows: type of field; method of disposal of secondary power; use of commutators; method of magnetization; method of connection.

Discussion (including that of paper by V. A. Fynn), pages 1416-1428, by Messrs. A. S. McAllister, H. M. Hobart, C. R. Underhill, C. A. Adams, V. A. Fynn, W. C. Korthals Altes and F. Creedy.

A general discussion of various methods of classification of electromagnetic machinery.

CLASS RATES FOR LIGHT AND POWER SYSTEMS OR TERRITORIES

Frank G. Baum **Vol. xxxiv—1915, pp. 1693-1713**

Arguments in support of the principle of establishing uniform rates throughout a system or territory for different classes of service. In establishing the rates, the author segregates the services into eight different classes and divides the rates into energy and demand charges.

Discussion, pages 1714-1729, by Messrs. A. H. Babcock, W. J. Norton, H. L. Wallau, M. G. Lloyd, S. N. Clarkson, W. H. Pratt, E. L. Wilder, J. W. Welsh, H. M. Hobart, R. W. Pope and F. G. Baum.

Discussion includes arguments for and against the class rate and statements of methods of rate making that have proved successful.

PROGRESS IN THE IRON AND STEEL INDUSTRY AND THE ELECTRIC FURNACE

Karl Georg Frank **Vol. xxxiv—1915, pp. 1731-1738**

The history and development of the electric furnace and a prophecy as to future development.

No discussion.

SYMPOSIUM ON "INVENTORIES AND APPRAISALS OF PROPERTIES"

Part I

C. L. Cory **Vol. xxxiv—1915, pp. 2023-2030**

The chief factors that must be taken into account in making an inventory and appraisal of an electric lighting and power property; the factors usually universally recognized; the factors generally recognized; the factors regarding which there is serious controversy; differences in inventories and appraisals of properties when these are to be used for different purposes.

Discussion incorporated with that of Part III by William J. Norton.

SYMPOSIUM ON "INVENTORIES AND APPRAISALS OF PROPERTIES"

Part II

W. G. Vincent, Jr. **Vol. xxxiv—1915, pp. 2031-2040**

The procedure that is necessary to obtain reliable inventories and reasonable appraisals of properties that can be defended both from the standpoint of the public and companies; the extent to which detailed inventories and appraisals should be kept up to date by companies; the best way in which detailed inventories and appraisals may be kept up to date by companies.

Discussion incorporated with that of Part III by William J. Norton.

SYMPOSIUM ON "INVENTORIES AND APPRAISALS OF PROPERTIES"

Part III

William J. Norton **Vol. xxxiv—1915, pp. 2041-2050**

Factors and items involved in the determination of working capital

Discussion (including that of Parts I and II, by C. L. Cory and W. G. Vincent, Jr.), pages 2051-2078, by Messrs. Philander Betts, H. Spoehrer, H. Floy, W. F. Lamme, F. J. Rankin, H. J. Ryan, F. E. Hoar, J. B. Fisken, J. H. Finney, D. B. Rushmore, L. B. Ready and C. L. Cory.

Discussion covers overhead charges, value of inventories, working capital, valuation and general related topics.

RATES AND RATE MAKING

Paul M. Lincoln **Vol. xxxiv—1915, pp. 2279-2318**

The necessity of recognizing load factor in rate schedules is emphasized. To obtain load factor necessitates the measurement of maximum demand; a new maximum demand meter is described which depends upon heat and heat storage. The theory of such meters is discussed. A new method of measuring power factor and volt-amperes is disclosed and a method of recognizing power factor in the rate for electric service is discussed.

Discussion, pages 2319-2360, by Messrs. W. McClellan, E. J. Cheney, P. Betts, J. W. Lieb, H. G. Stott, C. I. Hall, J. B. Taylor, H. W. Peck, H. Goodwin, Jr., W. N. Polakov, T. Jones, A.W. Burke, F.T. Leilich, R. S. Hale, E. J. Blake, A. Dow, J. G. De Remer, F. A. Sager, E. P. Roberts,

R. A. Philip, H. L. Wallau, R. A. Lundquist, J. D. Mortimer, L. R. Lee and P. M. Lincoln.

A general discussion for and against various methods of rate making.

THE COMBINED OPERATION OF STEAM AND HYDRAULIC POWER IN THE PENNSYLVANIA WATER AND POWER COMPANY SYSTEM

John Abbet Walls **Vol. xxxiv—1915, pp. 2361-2368**

The experience of a large hydroelectric development on an erratic river, in endeavoring to accomplish most effective combined steam and hydroelectric operation. A plea is made for drawing up power contracts to encourage effective combined operation of hydroelectric plant with customers' existing steam equipment.

Discussion incorporated with that of paper by J. F. Vaughan on "Supplemental Power for Hydroelectric Systems."

SUPPLEMENTAL POWER FOR HYDROELECTRIC SYSTEMS

J. F. Vaughan **Vol xxxiv—1915, pp. 2369-2381**

An outline of the functions of a steam plant furnishing relay and supplemental power for a system whose normal source of power is water. Diagrams illustrate in a hypothetical case the division of load between the hydraulic and supplemental sources of power.

The paper also discusses some general data obtained from a number of New England water power systems.

Discussion (including that of paper by J. A. Walls) pages 2382-2388, by Messrs. A. S. Loizeaux, Mr. Birkhinhine, and J. F. Vaughan.

A general discussion of the limiting factors in water power development.

CONSTRUCTION ELEMENTS OF THE TALLULAH FALLS DEVELOPMENT

Charles G. Adsit and W. P. Hammond **Vol. xxxiv—1915, pp. 2389-2438**

A very complete description of the Tallulah Falls hydroelectric development, one of the highest head water power plants in the world. Unit costs of the various items of construction are given.

Discussion, pages 2439-2442, by Messrs. A. J. Porskievies, A. S. Loizeaux, C. G. Adsit, C. O. Lens, Mr. Biglow, G. A. Hoadley, H. Pender, R. B. Owens and L. Jorgensen.

A general discussion of the details and unit costs of construction.

THE REPULSION START INDUCTION MOTOR

James L. Hamilton **Vol. xxxiv—1915, pp. 2443-2474**

This paper sets forth the general characteristics of the repulsion start induction motor and compares them with similar characteristics of d-c. motors and other a-c. motors. It outlines a definite and commercially practicable method of studying the electrical design of existing motors and of predetermining the design of new or proposed motors.

Discussion, pages 2475-2482, by Messrs. H. Weichsel, C. A. Weber, F. J. Bullivant, M. Brooks and J. L. Hamilton.

A general discussion of the design methods given by the author.

SINGLE-PHASE SQUIRREL-CAGE MOTOR WITH LARGE STARTING TORQUE AND PHASE COMPENSATION

Val A. Fynn **Vol. xxxiv—1915, pp. 2483-2508**

A description of a new single-phase motor which develops a large starting torque and operates with unity power factor. It outlines the manner in which the machine was developed, discusses the theory of its operation as well as novel points in its design and gives a number of test results obtained with motors of different sizes.

Discussion, page 2509, by Mr. H. Weichsel.

A brief description of the working characteristics of the motor.

MUNICIPAL CO-OPERATION IN PUBLIC UTILITY MANAGEMENT

P. J. Kealy **Vol. xxxiv—1915, pp. 2533-2544**

Conditions surrounding early grants and the meagre knowledge of the importance of public utilities in their inception. The changing view of the public and the constantly increasing investment necessary to meet demands. The need of favorable conditions that capital may be attracted. The question of regulation of utilities and the limitation of extensions. The injustice of diverting public utility earnings to municipal purposes. An abstract of the Kansas City traction ordinance.

Discussion, pages 2545-2548, by Messrs. C. A. Hobein, M. G. Lloyd, L. B. Cherry, N. W. Storer and P. J. Kealy.

Various views of the public utility and conditions surrounding them.

RECENT RESULTS OBTAINED FROM THE PRESERVATIVE TREATMENT OF TELEPHONE POLES

F. L. Rhodes and R. F. Hosford **Vol. xxxiv—1915, pp. 2549-2593**

The results of an experience with treated poles over a period of 18 years are analyzed. Data given for poles treated by pressure, open tank and brush methods. Rates of decay, increase in life by treatment, the effect of seasoning, and characteristics of the damage to poles caused by decay and by insects are covered.

Discussion, pages 2594-2600, by Messrs. H. von Schrenk, C. H. Teesdale, C. A. Hobein, Jr., L. B. Cherry, N. W. Storer and R. F. Hosford.

General discussion.

DECOMPOSING MAGNETIC FIELDS INTO THEIR HIGHER HARMONICS

H. Weichsel **Vol. xxxiv—1915, pp. 2721-2738**

A description of methods of decomposing a magnetic field into its higher harmonics by representing the field shapes as geometrical figures composed of a number of triangular waves with certain phase displacements against the other. This avoids in many cases the usual long mathematical operations. Equations are deduced for the harmonics of various wave shapes based upon Fourier's equation for a triangular field.

Discussion, pages 2739-2745, by Messrs. G. R. Dean, J. L. Hamilton, N. S. Diamant, L. W. Chubb and H. Weichsel.

A general discussion of the methods employed by the author in decomposing magnetic fields.

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THE MULTIPLEX COST AND RATE SYSTEM

BY OTTO B. GOLDMAN

ABSTRACT OF PAPER

The author gives the method of determining the cost of service having a variable demand, with special application to electric service, because the cost does and must always determine the selling price; competition and commissioners can only regulate the profit therein contained. Competition is destructive, involving an immense amount of unnecessary expenditure and lost motion. In order to insure the lowest price to the consumer we must have regulation, and monopoly. The author starts with the premise that an equipment must earn its cost and profits when in use; certainly it cannot do so when idle. The greater the percentage of total time an equipment or part thereof stands idle, the more it must earn when in use, because interest, etc., runs continuously. The subject is a big one and of tremendous import not only to the electric business, but to all business, and it has been the center of discussion for many years. It is now time to get down to absolute proofs of every conclusion, based upon fundamental facts.

THE SUBJECT of rates has received much attention of late, due naturally to its importance, and consequently many "systems" more or less related have been devised. A system is simply an attempt to straight-jacket judgment and make it all good. It must be correct or it is worse than none, and in order to be so, there must appear in the derivations no unbased assumption, such as are so often found. It must be apparent at once that no rate system can really be devised until a cost system has been obtained. For cost governs price, competition—and railroad commissions—only the profit therein contained. The multiplex cost system is a means of determining the cost of a variable service such as power service, gas, transportation, etc. In presenting this, I wish to acknowledge my indebtedness to the ability and patience of Mr. F. D. Weber, for valuable assistance. We are presenting the following only in its application to electric power service.

The demand for electric power service varies greatly during the day, from a very light night load, a tolerable day load, to an excessive peak load. Besides this we have seasonal variations of load. That must mean that part of our equipment is idle or only partly used during the day and year. We have here assumed that an equipment must pay for itself when in use—certainly it cannot do so when idle. As usual, we consider our costs as divided into two parts: (1) fixed charges, being all costs pertaining to an equipment when standing idle, and (2) operating costs, being all additional costs. It is evident that the first are continuous, the latter intermittent, depending on use. But the entire or total fixed charges for the year must be paid for during those hours in the year that the equipment is in use. Thus if F represents the fixed charges per year of a given equipment and N the number of hours in the year that the equipment is used, then F/N is the fixed charge cost per hour. This becomes $F/24 \times 365$ only when the plant is in continuous use.

DAILY VARIATIONS

In actual power service, we have primarily to consider the load variations during the day. In treating this variation, we consider the day divided into a number of periods. The greater the number of periods the more exact our results may be made, but the more intricate. Where we have two periods, we have the duplex system; where three, the triplex, etc. The latter we will now treat, calling the three periods the night, day and peak periods. Let us call M_1 the maximum demand during the night period, K_1 the mean demand, and N_1 the duration in hours of the night period; similarly M_2, K_2 and N_2 for the day period and M_3, K_3 and N_3 for the peak period, where $N_1 + N_2 + N_3 = 24$. We consider the total number of customers as divided into three classes according to the periods in which they demand service, charging each class with the cost burden that it places on the equipment, except as modified by the relation of one period to the others. In the above the night customers need an equipment of size M_1, the day customers one of size M_2 and the peak customers one of size M_3. Since $M_1 < M_2 < M_3$, the equipment of size M_1 is needed throughout the 24 hours, that of size $M_2 - M_1$ for $N_2 + N_3$ hours and that of size $M_3 - M_2$ for N_3 hours. For the present we will assume that the conditions assumed above are the same for each day of the year. Later we will consider seasonal variations.

Let us call C the cost of equipment per kw. and P the per cent of fixed charges, per year, so that CP becomes the fixed charge cost per kw-year. For the night period size we have $M_1\ CP$ as the total annual fixed charges and since this part of the equipment is in use 24 hours per day the fixed charge cost per hour becomes $M_1CP/365 \times 24$ or $M_1CP/365 \times 24\ K_1$ per kw-hr., so that we have for the fixed charge cost per hour

$$R'_1 = \frac{M_1CP}{365 \times 24 \times K_1} = \frac{M_1CP}{365 \times (N_1 + N_2 + N_3)\,K_1} \tag{1}$$

During the day period we have for the total fixed charge cost per hour

$$\frac{M_1CP}{365\,(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)\,CP}{365\,(N_2 + N_3)}$$

Dividing this by the mean load during this period we get

$$R'_2 = \frac{CP}{365\,K_2}\left[\frac{M_1}{(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)}{(N_2 + N_3)}\right] \tag{2}$$

which is the fixed charge cost for this period. During the peak period we have for the total cost per hour

$$\frac{M_1CP}{365\,(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)\,CP}{365\,(N_2 + N_3)} + \frac{(N_3 - M_2)\,CP}{365\,N_3}$$

whence the fixed charge cost per kw-hr. becomes

$$R'_3 = \frac{CP}{365\,K_3}\left[\frac{M_1}{(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)}{(N_2 + N_3)} + \frac{(M_3 - M_2)}{N_3}\right] \tag{3}$$

If now we call O_1 the operating cost per hour during the night period, O_2 and O_3 those during the day and peak periods respectively, then our costs (total) per kw-hr. become for the night, day and peak respectively:

$$R_1 = \frac{CP}{365\,K_1}\left[\frac{M_1}{(N_1 + N_2 + N_3)}\right] + \left[\frac{O_1}{K_1}\right] \tag{4}$$

$$R_2 = \frac{CP}{365\,K_2}\left[\frac{M_1}{(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)}{N_2 + N_3}\right] + \frac{O_2}{K_2} \tag{5}$$

$$R_3 = \frac{CP}{365\,K_3}\left[\frac{M_1}{(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)}{(N_2 + N_3)} + \frac{(M_3 - M_2)}{N_3}\right] + \frac{O_3}{K_3} \qquad (6)$$

This is, as stated above, on the basis of continuous use at the rates stated throughout the year.

Seasonal Variations

Taking into oonsideration the variations of load during the year we will usually find a comparatively light summer load, a medium spring and fall load and a very heavy winter load. That means that not only must part of our plant be idle part of each day, but that part of our equipment must lie idle often for months at a time, due to the above-mentioned conditions. Again, as above, in the daily load variations, the aggregate of those customers causing any special burdens on the equipment must pay for the burden they create by their demand. To determine this, we proceed as follows. Consider the year as divided into, say, three periods, the minimum of D_1 days duration, the mean of D_2 days duration, and the maximum of D_3 days duration. As above, let us call M_1, M_2 and M_3 the maximum demands for the night, day and peak periods respectively of the first or minimum period of the year, similarly K_1, K_2, and K_3 the mean demands in kw., and N_1, N_2, and N_3 the lengths in hours of the night, day and peak periods, where $D_1 + D_2 + D_3 = 365$. Then for this minimum period, the equations (4), (5) and (6) again hold.

For the mean period, let us call

M_1', M_2', and M_3', the maximum demands
K_1', K_2', and K_3', the mean demands
N_1, N_2, and N_3, the length in hours, and
O_1', O_2', and O_3' the operating cost per hour of the night, day and peak periods respectively. Then during the night period we have for the cost per hour

$$\frac{M_1 CP}{(D_1 + D_2 + D_3)\,(N_1 + N_2 + N_3)} + \frac{M_1' - M_1}{(D_2 + D_3)\,(N_1 + N_2 + N_3)} + O_1'$$

whence the cost per kw-hr. is

$$R_1' = \frac{CP}{(N_1 + N_2 + N_3)\,K_1'}\left[\frac{M_1}{D_1 + D_2 + D_3} + \frac{M_1' - M_1}{D_2 + D_3}\right] + \frac{O_1'}{K_1'} \qquad (7)$$

During the day period, we have for the cost per hour

$$\frac{M_1CP}{(D_1 + D_2 + D_3)\,(N_1 + N_2 + N_3)} + \frac{(M_1' - M_1)\,CP}{(D_2 + D_3)\,(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)\,CP}{(D_1 + D_2 + D_3)\,(N_2 + N_3)} + \frac{M_2' - M_2\,CP}{(D_2 + D_3)\,(N_2 + N_2)} + O_2'$$

whence the cost per kw-hr. becomes

$$R_2' = \frac{CP}{K_2'}\left\{\frac{1}{(N_1 + N_2 + N_3)}\left[\frac{M_1}{D_1 + D_2 + D_3} + \frac{M_1' - M_1}{D_2 + D_3}\right] + \frac{1}{(N_2 + N_3)}\left[\frac{M_2 - M_1}{D_1 + D_2 + D_3} + \frac{M_2' - M_2}{D_2 + D_3}\right]\right\} + \frac{O_2'}{K_2} \qquad (8)$$

During the peak period, we have for the cost per hour

$$\frac{M_1CP}{(D_1 + D_2 + D_3)\,(N_1 + N_2 + N_3)} + \frac{(M_2 - M_1)\,CP}{(D_1 + D_2 + D_3)\,(N_2 + N_3)} + \frac{(M_3 - M_2)\,CP}{(D_1 + D_2 + D_3)\,N_3} + \frac{(M_1' - M_1)\,CP}{(D_2 + D_3)\,(N_1 + N_2 + N_3)} + \frac{(M_2' - M_2)\,CP}{(D_2 + D_3)\,(N_2 + N_3)} + \frac{(M_3' - M_3)\,CP}{(D_2 + D_3)\,N_3} + O_3'$$

Dividing this by the mean load, we get

$$R_3' = \frac{CP}{K_3'}\left\{\frac{1}{(N_1+N_2+N_3)}\left[\frac{M_1}{(D_1+D_2+D_3)}\right.\right.$$

$$\left.+\frac{(M_1'-M_1)}{(D_2+D_3)}\right]+\frac{1}{(N_2+N_3)}\left[\frac{M_2-M_1}{D_1+D_2+D_3}\right.$$

$$\left.+\frac{M_2'-M_2}{D_2+D_3}\right]+\frac{1}{N_3}\left[\frac{M_3-M_2}{D_1+D_2+D_3}\right.$$

$$\left.\left.+\frac{M_3'-M_3}{D_2+D_3}\right]\right\}+\frac{O_3'}{K_3'} \tag{9}$$

For the maximum period let us call

M_1'', M_2'', and M_3'', the maximum demands
K_1'', K_2'', and K_3'', the mean demands
N_1, N_2, and N_3, the length in hours, and
O_1'', O_2'' and O_3'', the operating costs per hour of the night, day and peak periods respectively of this maximum period. Then during the night period of this season, we have for the cost per hour

$$\frac{M_1CP}{(N_1+N_2+N_3)(D_1+D_2+D_3)}+\frac{M_1'-M_1}{(N_1+N_2+N_3)(D_2+D_3)}$$

$$+\frac{M_1''-M_1'}{(N_1+N_2+N_3)D_3}+O_1''$$

Whence the cost per kw-hr. is

$$R_1'' = \frac{CP}{(N_1+N_2+N_3)K_1''}\left[\frac{M_1}{(D_1+D_2+D_3)}+\frac{(M_1'-M_1)}{(D_2+D_3)}\right.$$

$$\left.+\frac{M_1''-M_1'}{D_3}\right]+\frac{O_1''}{K_1''} \tag{10}$$

Similarly we get, for the cost per kw-hr. during the day period,

$$R_2'' = \frac{CP}{K_2''} \Bigg\{ \frac{1}{(N_1 + N_2 + N_3)} \Bigg[\frac{M_1}{D_1 + D_2 + D_3} + \frac{M_1' - M_1}{D_2 + D_3}$$

$$+ \frac{M_1'' - M_1'}{D_3} \Bigg] + \frac{1}{(N_2 + N_3)} \Bigg[\frac{(M_2 - M_1)}{(D_1 + D_2 + D_3)}$$

$$+ \frac{M_2' - M_2}{(D_2 + D_3)} + \frac{M_3'' - M_2'}{D_3} \Bigg] \Bigg\} + \frac{O_2''}{K_2''}$$

and for the peak period

$$R_3'' = \frac{CP}{K_3''} \Bigg\{ \frac{1}{(N_1 + N_2 + N_3} \Bigg[\frac{M_1}{(D_1 + D_2 + D_3)} + \frac{(M_1' - M_1)}{(D_2 + D_3)}$$

$$+ \frac{M_1'' - M_1'}{D_3} \Bigg] + \frac{1}{(N_2 + N_3)} \Bigg[\frac{(M_2 - M_1}{(D_1 + D_2 + D_3)}$$

$$+ \frac{(M_2' - M_2)}{(D_2 + D_3)} + \frac{(M_2'' - M_2')}{D_2} \Bigg] + \frac{1}{N_3} \Bigg[\frac{M_3 - M_2}{(D_1 + D_2 + D_3)}$$

$$+ \frac{(M_3' - M_3)}{(D_2 + D_3)} + \frac{M_3'' - M_3'}{D_3} \Bigg] \Bigg\} + \frac{O_3''}{K_3''}$$

For brevity's sake we are leaving out, for the present, the case of more than three periods in the year and the rather important condition where in each of the seasonal periods, the corresponding periods of the day are different, *i.e.*, where we have for the length of the night, day and peak periods, N_1, N_2 and N_3 during the minimum period, $N_1{,}'$ N_2' and N_3' during the mean period, and N_1'', N_2'' and N_3'' during the maximum period. We will instead proceed at once to show the application of a concrete example under the first case. This application is merely illustrative.

APPLICATION OF CASE I

In computing the cost of power in the following, we have segregated each factor contributing thereto; *i.e.*, generation, transmission, transformation, and distribution. This must be done in every practical example, as it usually happens that we have customers taking power directly at the power house, or along the transmission line, who naturally would not be chargeable for that part or parts of our entire equipment that is not needed to serve them. Let us assume then that we have at the generating plant the following conditions:

4000 kw. maximum demand in the night period
13000 " " " " " day "
20000 " " " " " peak "
4000 kw. mean demand night period
10000 " " " day "
18000 " " " peak "

7 hours duration of night period
11 " " " day "
6 " " " peak "

So also cost of generating plant and step-up transformers per kw. of capacity $150.00, and per cent of fixed charges (annual) 13 per cent. Then our fixed charges are

150×13% = $19.50 per kw-year, or
19.50/365 = $0.0534 per kw-day.

Reasonable consideration must be taken of the future, so that a growth factor must be allowed, because increases must be made in reasonable size units. What a reasonable growth factor is can only be determined in each individual case. In any plant under consideration, that growth factor actually existing should be allowed unless it is apparently unreasonable. Let us assume that this growth factor in our case is 20 per cent, then we have for our fixed charges $0.06408 per kw-day, which becomes 0.06408/24 or $0.00267 per kw-hr. for the night period.

During the day period we have for our cost per hour

(4000 × $0.00267 + 13,000 − 4000) × $0.06408/17 or $44.61

The mean load being 10,000 kw., we get for the fixed charges

44.61/10,000 or $0.004461 per kw-hr.

During the peak period, we have for the cost per hour

20,000 − 13,000 × 0.06408/6 + 9000 × 0.00377 + 4000 × 0.00267, or $119.37.

Since our mean load is 18,000 kw., we get for our fixed charges 119.37/18,000 or $0.00663 per kw-hr.

If our operating costs are

$0.00020 for the night period, per kw-hr.
0.00014 " " day " " " and
0.00011 " " peak " " "

then our total production cost per kw-hr. becomes

0.0002 + 0.00267 = 0.00287 for the night period
0.00014 + 0.004461 = 0.004601 for the day period
0.00011 + 0.00663 = 0.00674 for the peak period.

For the transmission line we will assume a cost of 25 cents per kw-mile with a fixed charge cost of 15 per cent, and 50 miles of transmission to the first substation. Then the fixed charge cost per kw-mile-year is 0.25 × 0.15 = 0.0375, and per day is

0.0375 / 365 = 0.000103, which becomes for the total 50 miles, after allowing for the growth factor as before,

(0.000103 × 50) 1.20 = 0.00618 per kw-day.

For the night period then we have

0.00618/24 = 0.000258, the fixed charge cost per kw-hr.

During the day period, we have the cost per kw-hr. for the added equipment. The added equipment is

13,000 − 4000 = 9000 kw., whence the cost per hour is
9000 × 0.000363 = $3.267 +
4000 × 0.000258 = $1.032

or a total of $4.299. Whence the fixed charge cost per kw-hr. is

4.299/10,000 = $0.0004299

During the peak period, we have for the added equipment the fixed charge cost per kw-hr. of 0.00618/6, or 0.00103. The added equipment is

20,000 − 13,000 = 7000 kw., whence we have
7000 × 0.00103 = $7.21 +
9000 × 0.000363 = 3.267 +
4000 × 0.000258 = 1.032 or a total of $11.509

Whence the fixed charge cost per kw-hr. is

11.509/18,000 or $0.0006394

Taking for the operating costs per kw-hr. the following:

$0.00002778 during the night,
0.00001667 during the day and
0.00001125 during the peak, we get for the total transmission costs per kw-hr.:

0.000258 + 0.00002778 or $0.00028578 for the night
0.00001667 + 0.0004299 or $0.00044657 for the day
0.00001125 + 0.0006394 or $0.00065065 for the peak period.

We now come to the substation No. 1. Suppose here we have for maximum demands

1000 kw. during the night period
2000 " " " day " and
4000 " " " peak "

and for the mean demand

900 kw. during the night
1500 " " " day, and
3600 " " " peak period

The length of each period being taken as before, while the cost or investment per kw. at the substation is taken at $15.00 and the per cent of fixed charges per year is taken at 10, then the fixed charge cost per kw-year is 15.00 × 10 per cent, or $1.50, while the fixed charge cost per kw-day becomes, after allowing for growth factor as before,

(1.50/365) 1.20, or, $0.00492.

For the night we have for the cost per kw-hr.

(0.00492/1000)/(24 × 900) or $0.000228.

For the day period we have for the fixed charge cost per hour

(2000 − 1000) × 0.00492/17 or $0.29 +
1000 × 0.000205 or 0.205, or a total of $0.495, *i. e.*,
0.495/1500 or $0.00033 per kw-hr.

During the peak period, we have for the fixed charge cost per hour

(4000 − 2000) × 0.00492/6 or $1.64 +
1000 × 0.00029 or $0.29 +
1000 × 0.000205 or $0.205, or a total of $2.135

Whence the cost per kw-hr. becomes

2.135/3600 or $0.000593.

If our operating costs at the station are

0.00067 per kw-hr. during the night,
0.000417 per kw-hr. during the day, and
0.00028 per kw-hr. during the peak period,

then we have for our total substation costs

0.00067 + 0.000228 = $0.000898 per kw-hr. (night period)
0.000417 + 0.00033 = 0.000747 " " (day period)
0.00028 + 0.000593 = 0.000873 " " (peak period)

Summarizing to substation No. 1, we have:

During the night period

Generating cost per kw-hr.	$0.00287
Transmission " " "	0.0002858
Substation " " "	0.000898
Total	0.0040538

which at 95 per cent efficiency becomes $0.00416 per kw-hr.

During the day period, we have

Generating cost per kw-hr.	$0.0046
Transmission " " "	0.0004467
Substation " " "	0.000747
Total	$0.005793,

which at 95 per cent efficiency becomes $0.0061 per kw-hr.

During the peak period, we have

Generating cost per kw-hr.	$0.00674
Transmission " " "	0.00065065
Substation " " "	0.000873
Total	$0.00826365

which at 95 per cent efficiency becomes $0.0087 per kw-hr.

If the distance from substation No. 1 to substation No. 2 is 50 miles, that will make our total distance, from the generating plant to substation No. 2, 100 miles, so that, other conditions being assumed equal, our transmission cost to substation No. 2 will be double that to substation No. 1, or

$0.000572 per kw-hr. for the night period
0.000892 " " " " day "
0.0013 " " " " peak "

At substation No. 2 we have for the maximum demands

3000 kw. during the night,
11000 kw. during the day, and
16000 kw. during the peak period.

Mean demands

3000 kw. during the night,
8500 kw. during the day, and
14400 kw. during the peak period.

Investment $11.00 per kw. of capacity.

Fixed charges 10 per cent.

11.00 × 10 per cent = $1.10 fixed charge cost per kw-yr. or

1.10/365 = 0.003 per kw-day, which, allowing 20 per cent growth factor, gives $0.0036 per kw-day total.

Whence for the night period we have

0.0036/24 or $0.00015 per kw-hr.

During the day period we have

(11,000 − 3000) × 0.0036/17 = 1.69 and
3000 × 0.00015 = 0.45

or a total of $2.05, whence

2.05/8500 = 0.00025, fixed charge per kw-hr.

During the peak period, we have

(16,000 − 11,000) 0.0036/6	= $3.00
8000 × 0.00021	= $1.69
3000 × 0.00015	= $0.45
Total	$5.14

Whence the fixed charge cost per kw-hr. becomes

5.14/14,400 or $0.000357.

If the operating costs are

0.000263 per kw-hr. during the night,
0.000194 per kw-hr. during the day, and
0.000162 per kw-hr. during the peak,

then our total costs at substation No. 2 per kw-hr. become

0.000263 + 0.00015 = 0.000413 for the night
0.000194 + 0.000252 = 0.000446 for the day, and
0.000162 + 0.0003275 = 0.0004895 for the peak period.

The total costs to and including substation No. 2 then become for the night period

Generation	0.00287
Transmission	0.000572
Substation No. 2	0.000413
Total	0.003855

If the efficiency to and including substation No. 2 is 90 per cent this total becomes 0.004283 for the available power.

For the day period,

Generation	0.00461
Transmission	0.000892
Substation No. 2	0.000446
Total	0.005948

which at 90 per cent efficiency again becomes 0.006610.

For the peak period,

Generation	0.00674
Transmission	0.0013
Substation No. 2	0.0004895
Total	0.00853

which at 90 per cent efficiency becomes $0.00948.

DISTRIBUTION NO. 1 FOR SERVICE FROM SUBSTATION NO. 1

We have now to get the cost of our distribution system per kw-hr. Suppose here we have an investment of $100.00 per kw. and that the per cent of fixed charges is 12, then

100.00 × 12 per cent or $12.00 is the fixed charge cost per kw. per year,

or 12.00/365 = 0.33, the fixed charge cost per kw. per day,

and allowing 20 per cent for growth factor as before, our fixed charge per kw. per day becomes $0.0396.

For the night then we have

0.0396/24 = 0.00165

(0.00165 × 1000)/900 = 0.00183 fixed charge cost per kw-hr.

During the day we have

(2000 − 1000) × 0.0396/17 =	2.33
0.00183 × 1000 =	1.83
Total	4.16

4.16/1500 = $0.002774 per kw-hr.

During the peak period we have

(4000 − 2000) (0.0396)/6 =	$13.20
1000 × 0.00233 =	2.33
1000 × 0.00183 =	1.83
Total	$17.36

17.36/3600 = $0.00482 per kw-hr.

Assuming then that the operating costs per kw-hr. are

0.00049 during the night
0.00043 " " day, and
0.00038 " " peak period

then our total costs per kw-hr. become

0.00049 + 0.00183 = 0.00232 during the night
0.00043 + 0.002774 = 0.0032 during the day
0.00038 + 0.00482 = 0.0052 during the peak period.

If the efficiency of our distribution system is 90 per cent, then the above become for the total cost per kw-hr. of available power,

$0.0026 for the night period

0.00356 for the day period, and

0.00578 for the peak period.

The cost of the power to and including distribution per kw-hr. then is

0.0043 + 0.0026 = $0.0069 for the night period.

0.0061 + 0.00356 = 0.00966 for the day period.

0.00863 + 0.00578 = 0.01441 for the peak period.

DISTRIBUTION No. 2

From substation No. 2 we have distribution system No. 2. Suppose that the investment per kw. of capacity here is $90.00 and that the per cent of fixed charges is 11, then the fixed charges per kw-year are 90.00 × 11 per cent or $9.90 or $0.0271 per kw-day. Allowing again 20 per cent for growth factor, this becomes 0.0325.

For the night period then we have

0.0325/24 = 0.00135 fixed charges per kw-hr.

For the day period, we have

(11,000 − 3000) × 0.0325/17 = $15.20

3000 × 0.00135 . . . . = 4.05

Total 19.25

19.25/8500 = 0.00226 per kw-hr.

For the peak period we have

(16,000 − 11,000) × 0.0325/6 = $27.00

8000 × 0.0019 . . . . = 15.20

3000 × 0.00135 . . . . = 4.05

Total $46.25

46.25/14,400 = 0.0029 per kw-hr.

If the operation costs per kw-hr. are

0.000375 during the night

0.000325 during the day and

0.0003 during the peak period

then the total costs for distribution under system No. 2 are

0.000375 + 0.00135 = 0.001725 for the night.

0.000325 + 0.00226 = 0.002585 for the day.

0.0003 + 0.0029 = 0.0032 for the peak period.

At 90 per cent efficiency of our distribution system, these become

0.001917 for the night
0.00287 for the day
0.003555 for the peak period based on available power.

The total costs to and including distribution system No. 2 are

0.004283 + 0.001917 = 0.0062 for the night
0.00661 + 0.00287 = 0.00948 for the day
0.003555 + 0.00948 = 0.13 for the peak period.

THE MULTIPLEX RATE

Having determined the cost of service, we have now to determine the rate. In order that a rate be of practical use, it must be fairly simple, and in effect such that it redounds to the best interest of both the consumers and the power company. Let us first take up the matter of simplicity. In applying this rate, we add to the previously determined cost of service a certain percentage of allowable profit, which should depend on the efficiency of the system. In order then to apply the multiplex rate it seems that a time-wattmeter would be necessary for each installation, and this would be impracticable. But this is not at all necessary. The vast majority of small power users are residential light customers. The time when and the number of hours that they demand service, are practically the same for all of them. A test will show what percentage of their load is in each period, and knowing this we can at once calculate a flat rate per kw-hr., or per lamp, as we choose, based not on guesswork but on knowledge of the cost of that service and what that service consists of. So we can classify and give a flat rate to any service, as residential lighting, commercial, or street lighting, etc., that allows of group classification. In these cases we would actually simplify the rate, *i. e.*, for any given season, although we would have to vary the rate in each season to take care of the variation of the cost of service in the different periods of the year. In the remaining cases that do not allow of group classification, we would have to resort to time-wattmeters or agreements restricting usage without special permit. These would be mostly the larger power users.

In giving a rate based on cost of service, we are treating each and every customer impartially and are therefore creating a feeling of mutuality between the power company and the customers. That is a valuable asset. Not only that, but a rate based on cost automatically tends to discourage the use of power at such a time that it would tend to increase the average cost. It would tend to encourage the use of power at such times that the average cost would be reduced, *i. e.*, the demand would gravitate as much as physically possible to the time of lowest cost. This means that the valleys in the load curve will tend to fill up. Growth will be along natural, healthy lines, instead of artificial.

In an excellent résumé on rates, Mr. Stacy Hamilton presented before the Northwest Electric Light and Power Association at its joint meeting with the Pacific Coast meeting of the A. I. E. E., Spokane, Wash., September 9-11, 1914, a paper which not only aptly illustrates present-day rates but present-day incongruities—and some of these unwittingly. He states, for example, "There are two general basic theories on which a system of rates may be established, *i. e.*, the cost of service theory, and the value of service theory." He says further: "Under the cost of service theory we have, at one extreme, the attempt to differentiate in proportion to the exact cost to each individual condition of service. This must necessarily result in a schedule so complicated as to be entirely impracticable. At the other extreme we have a general average or uniform rate to all customers based on the general average cost of rendering service to all consumers." As a matter of fact there are at present neither rates based on the cost of service nor on the value of service. Before we can have a rate based on cost of service, we must know definitely the cost of service; before we can have a rate based on the value of service, we must definitely know the value of the service in each individual or group case. The value of a service is not what it costs but the profit it earns. For example, we may be manufacturing a certain article. Suppose that wages increase and at the same time the selling price of the article decreases. Then it is evident that the cost of the service has increased at the same time that the value of the service has decreased. So that before we could make a rate based on value of service, we would have to know in detail our customer's business. Such a rate would have to decrease in times of business depression and increase in good times. Under such a rate the value of service may decrease while the cost of service remains stationary or even increases. Such a rate does not exist nor ever will exist, for the reason that the fundamental basis of any charge must always be the cost; competition and commissions can only regulate the profits, to which the latter may add by way of regulation the proper distribution of the costs to individual or group cases.

Respecting rates based on cost of service, we have said that such do not exist, nor can they exist until the cost of service has been determined as is first done in this article. We have shown above that the application of a rate based on cost in the multiplex form, used with good judgment, is not any more complicated on the average than present rates. The so-called uniform rate is not based on the cost but only on average (annual) cost. Such rates cannot be in proportion to costs. An assumption that they are so would involve errors of over 100 per cent; that is, absolutely valueless results. Power service is a natural monopoly, *i. e.*, this service can berendered better and cheaper under such conditions than under competition. Competition then becomes a farce at the expense of the public. But having a monopoly, a distinction between " competitive " and " non-competitive " business becomes discrimination. Present rates are based on this, that they must collect enough annually to pay for the cost of service for the year, plus a profit that can be collected. With respect to the form of the rate so that a proper distribution of the charges may be made, there has been up to the present no basis whatever.

At present, commissions allow power companies annually the annual cost of service exclusive of interest on invested moneys and a certain return on the invested moneys, usually 8 per cent. Inasmuch as the cost of money is as definite as the cost of copper wire, it would seem to be better to determine the entire cost of service and then allow a certain percentage of profit or a commission for the execution of this service. And this commission should be in proportion to the efficiency of the system, the degree of wisdom and foresight displayed in necessary investments, the ability displayed in the development of business, etc.; in other words, the quality, price also considered, of the service. Thus an efficient power company should receive a greater return than an inefficient one.

It is time to develop in these matters along broad and permanent lines, and we trust this paper will assist in some degree in so doing. We have had to abbreviate the presentation greatly, but we hope not so much so, as to sacrifice clearness, so far as we have carried matters in this discussion.

DISCUSSION ON "THE MULTIPLEX COST AND RATE SYSTEM" (GOLDMAN), PORTLAND, ORE., JANUARY 5, 1915.

Julian Lobenstein (by letter): Mr. Goldman discusses what he calls growth factor. Just what does he mean by that term? It seems that since he increases the fixed charges in order to take care of future growth, he expects to make extensions from earnings. This has been done in the past, but will the public service commissions permit it in the future? In other words, according to modern practise, extensions should be made from capital, not from earnings. Of course, if the company is in a position to pay a fair dividend but prefers to invest the dividend moneys in extensions, capitalizing those expenditures, no commission would find fault; but it is far from likely that two charges will be allowed as part of the rate, one to take care of future extensions and another allowed, in itself large enough to yield a fair dividend.

That this is the stand taken is shown in the decision of the New York Public Service Commission, First District, in the case of the Queensborough Gas & Electric Light Co., decided June 23, 1911. Commissioner Maltbie says:

"Furthermore, it is not reasonable to require consumers to pay higher rates than they otherwise would be required to pay in order that these higher rates may provide funds from which to construct additional plant, which becomes the property of the company. Such plant and property is ordinarily paid for out of capital, but whether this course is followed or the stockholders voluntarily relinquish a share of their dividends in order to increase the value of their property, has no relation to this case. Suffice it to say that the consumer should not be required to pay higher rates and thereby make a donation to the company or to its stockholders."

And again in the case of the Central Yellow Pine Association vs. I.C.R.R.Co., 10 I.C.C. Rep. 505, the Insterstate Commerce Commission says:

" . . . . this Commission cannot properly permit an advance in rates with the intent to produce an accumulation of surplus for this purpose." (This purpose being the making of extensions.)

Perhaps Mr. Goldman means to use this 20 per cent charge for the amortization of inadequate and obsolescent machinery, machinery made inadequate by the growth of the plant. If that is the case, why not call it by a more descriptive and better known name? Why not call it depreciation reserve?

L. C. Tomlinson (by letter): The scientific investigation of the exact premises upon which to found *all* systems of charges for *all* public utilities is now attracting the thought of unbiased men outside of the employment of the companies supplying the public service or associated with companies in other fields of activity.

Until the last few years the subject of systems of charges has been discussed in printed articles or public addresses in almost every case by persons in some way allied with companies supplying the service under consideration. We find a man expounding his own views on a new rate just established by his company that will be more attractive to the consumer than all the rates now in existence; or an address will be given in which a number of rates that have proved the best business getters will be explained by concrete examples. However, in practically every case, these new rates have been only new methods of presenting the gross bill to the consumer; merely examples of the art of bill-making. In no case is the true fundamental system of charges given more than a passing thought.

Mr. Goldman takes for his foundation the exact premise that all systems of charges formed by purveyors of public utilities must be based upon the costs of supplying a specific utility. While he does not say so, he implies that the elements upon which the costs depend are demand, quantity and time. These three elements are the base of all systems of charges for all public utilities, as I have shown in an article in the *Electrical World*, vol. 63, page 830 (April 11, 1914).

In the "daily variations" and "seasonal variations" Mr. Goldman combines the demand and the time elements, daily and seasonal, to obtain the fixed charge cost and to this cost adds an operating cost which combines the quantity and time elements, daily and seasonal.

He has advantageously divided the time element into periods, but has forgotten that the other two fundamental elements can also be indefinitely divided. In his illustrations he has seriously handicapped himself by assuming that consumers are segregated into classes. No advantage is gained by making this hypothetical division of consumers. On the contrary it has a decided detrimental effect upon the soundness of the theory he is trying to establish. The reader is led to believe that there are and must be other methods of computing the cost for his other hypothetical classes of consumers. I cannot see why there need be any change in the text if any one of the various classifications so commonly used by supply companies were substituted in place of the class that the author has designated by the word "power."

After Mr. Goldman has so admirably developed his theory for determining the cost of service he begins to hunt excuses for the impracticability of the theory he has established and the methods of application. He finally seeks cover under the timeworn cloak of averages, and allows himself to follow the path of least resistance by taking a "flat rate" for any service.

The time-wattmeter that the author thinks so impractical is not a new instrument. At present there are upon the market a number of feasible time-watt-hour meters that are accurate and not costly. In fact they cost no more than the earlier watt-hour meters did when they were first placed in commercial service.

No doubt the companies manufacturing wattmeters will develop any class of meter at a reasonable cost just as soon as a company supplying a public utility service desires it. The manufacturing companies, in truth, generally lead the demand of the supply companies in new equipment.

O. B. Goldman: In going over Mr. Loebenstein's discussion, we are forced to the conclusion that he has misunderstood what is meant by growth factor, for we certainly agree with his conclusion that no company has the right or privilege to charge the public for extensions or new construction or additions on which thereafter they may charge interest, profit, etc. We have placed ourselves on record as to this point in a talk some three years ago before the annual convention of the Idaho Society of Engineers at Weiser, Idaho (vid. Proceedings Idaho Soc. of Eng., No. 1, Vol. III).

What is meant by growth factor is this: Suppose a given plant consists of three 3000-kw. generators that have now reached full load, and that there is a demand for another 1000 kw. It would be more advisable to install another 3000-kw. unit and be in position to take care of still further growth than just to install a 1000-kw. unit; and the same thing is still more true of line construction. Who then, should pay for this idle part, *i.e.*, the interest, etc., charges on it? If the company must, then it will not be done and the public will in the end have to pay high for lack of foresightedness on the part of the company. The public should therefore pay this, for the company is merely the agent of the community it serves, to be paid in proportion to the quality or lack of quality of its service. We certainly do not mean depreciation reserve.

Mr. Tomlinson's opening statement is interesting and no doubt based on personal observation. Naturally those engaged in a certain business are best qualified to first discuss problems allied to that business. He states that I imply the elements of demand, quality and time, referring to an article of his in the *Electrical World* of April 11, 1914.

The first article on this was published by us Jan. 17, 1914, in the *Journal of Electricity Power and Gas* of San Francisco, Cal. Mr. Tomlinson's letter to the *Electrical World*, referred to above, we found to be all generalities, and that he defined demand, quantity and time as follows:

"The demand that the consumer is likely to make on the supplying company

"The quantity of the commodity or service that the consumer takes or uses, and

"The time at which the consumer makes the demand, and the quantity then taken and used."

The elements that I use refer to the aggregate of all customers, so that customers obtain a certain rate per period

Therefore customers having the same demand, quantity and time take different rates if under different systems where the aggregates are different. Furthermore, I do not imply the elements I use, but indicate each clearly by symbol that I use in my cost calculation, and their definitions are given definitely. All the elements as I define them in all my calculations should therefore be evident.

He then makes the following unsupported statements, that we have "forgotten that the other two elements (demand and quantity) can also be indefinitely divided" and that we have "seriously handicapped" ourselves by segregating customers into classes.

We cannot get anywhere, without starting from an agreed premise and thence step by step, each fully proved, to our conclusions.

Mr. Tomlinson concludes by saying that "after Mr. Goldman has so admirably developed his theory for determining the cost of service he begins to hunt excuses for the impracticability of the theory he has established and the methods of application." Certainly Mr. Tomlinson must know that there is a wide difference between the development of a theory and its practical application. The latter requires much good judgment, knowledge of human nature and of existing conditions. It certainly is poor judgment to spend 25 cents to bill a 15-cent charge. We have not attempted a solution of the practical application of the multiplex cost and rate system. A theory is merely a compass to guide the application in the right general direction. We have merely sketched a possible outline based upon criticism and suggestions of such men as Mr. Caldwell, gen. supt. of the Portland Ry. Lt. & Pr. Co., Mr. Max Thelen, president, R. R. Commission of California, Mr. Mervin, engineer of the Northwestern Elec. Co., and other men of unusual ability and knowledge in this line, covering a period of over two years. You will therefore find the suggestions in the latter part valuable, the group classification absolutely good and necessary, but much, very much, remains to be done.

Presented at the 303rd meeting of the American Institute of Electrical Engineers, New York, January 8, 1915.

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THEORETICAL INVESTIGATION OF ELECTRIC TRANSMISSION SYSTEMS UNDER SHORT-CIRCUIT CONDITIONS

BY I. W. GROSS

ABSTRACT OF PAPER

The following features of a transmission system under short-circuit conditions are discussed:

1. Mechanical forces between the phases of three-conductor, three-phase cables when carrying short-circuit current; also the forces between busbars are investigated.
2. The heating of the conductors of the cable from the instant of short circuit to a time 0.8 seconds later is traced analytically, during the transient state of the current, and typical computed heating curves are presented.
3. The effectiveness of the method of placing reactors between generator terminals and the bus from which power is taken, and additional reactors between generators and an auxiliary synchronizing bus, is analyzed.
4. This scheme is compared with the present well-recognized schemes of feeder and busbar reactors.

THE rapid growth of central stations in recent years with the constantly increasing power concentrated on one set of busbars has made necessary some method of protecting the system as a whole, and also its various parts, in case of abnormal conditions on the line. Reactance, which formerly was stringently avoided in central station electrical apparatus, is now being almost universally required in the apparatus itself, and in many cases additional reactance is supplied by reactors external to the electrical units.

In applying these reactors to central station design, much attention has been given, and several well-recognized schemes have been worked out and are now in operation.

The parts of the high-tension system for which protection must be furnished under short-circuit conditions are as follows:

1. Oil switches against absolute failure.
2. Generators, transformers, busbars and underground cables against mechanical forces.
3. All apparatus against overheating
4. The system as a whole against complete shut-down.

A system designed to provide protection against any three of the above cannot be considered ideal if it fails in the fourth; and it is only by limiting the short-circuit current to such a value in different parts of the circuit as to eliminate the above controlling factors that the use of reactance can be regarded as fully effective.

ULTIMATE OIL SWITCH CAPACITY

In the case of oil switch breaking capacity, it is possible at the present time to obtain a guarantee for switches to clear any trouble on an 11,000-volt, three-phase system with a running capacity of 70,000 kv-a. and a reactance of 10 per cent; that is, a short-circuit current of 36,800 r.m.s. amperes. It is, therefore, assumed from the foregoing guarantee, that any 11,000-volt system, where the short-circuit current does not exceed 36,800 amperes, will experience no inherent difficulty from oil switch trouble.

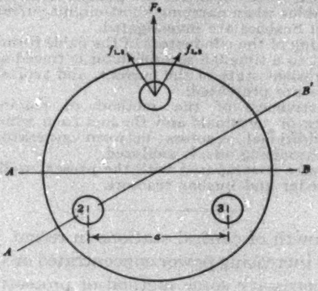

FIG. 1

MECHANICAL FORCES IN ELECTRICAL APPARATUS

This phase of the problem has been given careful attention of late, especially in generators, with the result that generators are now being built with such mechanical rigidity that manufacturers maintain they will safely withstand the mechanical forces arising from dead short circuit across their own terminals.

Modern transformers, likewise, are being more substantially built, so that it is unlikely that mechanical rupture will occur in them before some other limiting features of the system are exceeded.

Underground cables and busbars are subject to even heavier strains than the generators themselves, and an analysis of these stresses is here given.

FORCES BETWEEN CONDUCTORS OF THREE-PHASE CABLE

First, take a three-conductor cable, as shown in Fig. 1, with all three conductors equally spaced, and assume all three legs simultaneously short-circuited, and the r. m. s. current equal in each phase. Then the force tending to repel any conductor in a direction at right angles to a plane passing through the other two may be computed as follows:

Let the currents in all three phases, 1, 2 and 3, be sinusoidal. In Fig. 1, let $i_1 = I_m \sin \omega t$ = instantaneous current in phase 1.

$$i_2 = I_m \sin\left(\omega t + \frac{2\pi}{3}\right)$$

$$i_3 = I_m \sin\left(\omega t + \frac{4\pi}{3}\right)$$

I_m = maximum value of sine wave.

Then f_{1-3} = instantaneous force between conductors 1 and 3.

f_{1-2} = " " " " 1 " 2.

f_0 = " " on conductor 1 perpendicular to plane $A.B.$

$f_0 = (f_{1-3} + f_{1-2}) \cos 30$ deg.

$f_{1-3} = k\, i_1 i_3 / a.$

$f_{1-2} = k_1\, i_1 i_2 / a.$

k = numerical constant

F_0 = average force on conductor 1 perpendicular to plane $A\,B.$

$$F_0 = \int_0^{\frac{1}{n}} d f_0 = \frac{k\, n \sqrt{3}}{2a} \int_0^{\frac{1}{n}} (i_1 i_3 + i_1 i_2)\, dt$$

$$= -\frac{\sqrt{3}}{2\,a} k\, I^2$$

I = r. m. s. value of sine wave $= \dfrac{I_m}{\sqrt{2}}$

n = cycles per second.

$\omega = 2\pi n.$

If F_0 is in lb. per foot of cable and I in amperes

$k = 5.39 \times 10^{-7}$, a being in inches.

Hence $$F_0 = -\frac{4.67\, I^2\, 10^{-7}}{a \text{ (inches)}} \text{ lb. per foot} \qquad (1)$$

The negative sign appearing in the expression for the average force, F_0, means that the conductors under study are subject to repulsion. Thus, in a paper-insulated, lead-covered cable, the force is exerted on the over-all wrapping around all three conductors and also on the lead sheath; and the tensile strength of the paper and lead must be sufficient to withstand the stress thus placed upon them.

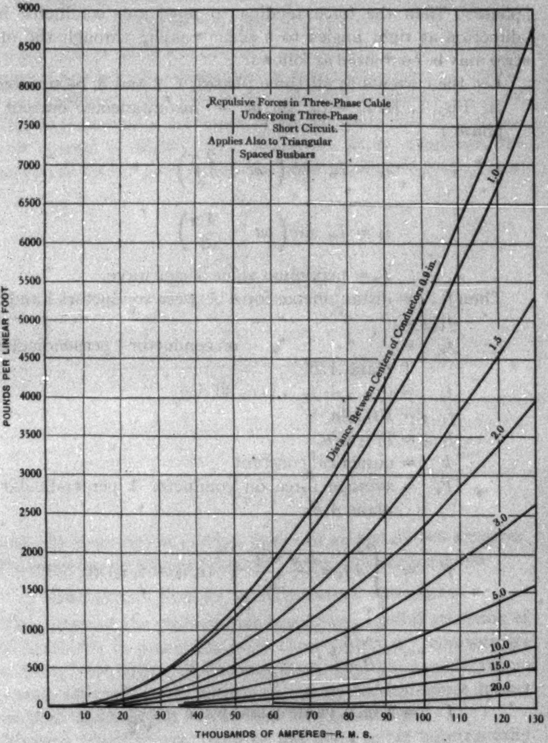

FIG. 2

On busbars this force tends to throw the busbar away from the center of the equilateral triangle (of which each busbar is assumed to form one apex) and produces tension or compression on the busbar clamps, depending on the location of the insulators.

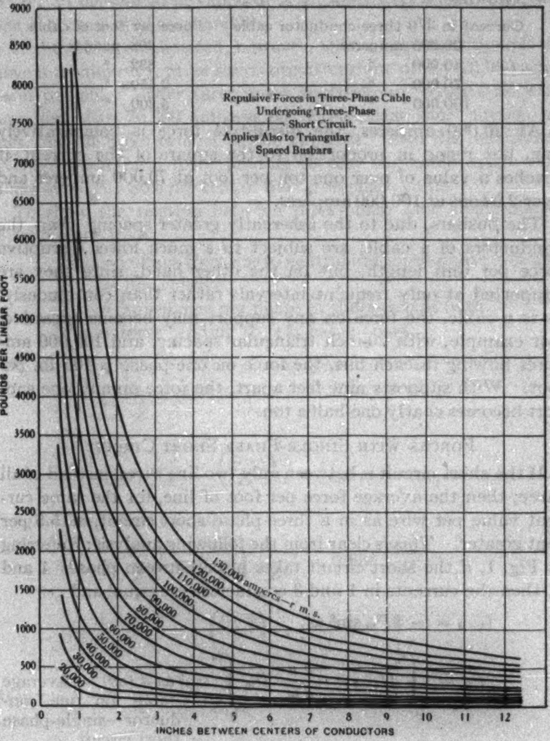

FIG. 3

From equation (1) the curves in Figs. 2 and 3 have been computed. The curve in Fig. 2 marked "0.9 inches between conductors" represents the varying average force on one conductor of a three-conductor 3/0 B. & S. paper-insulated lead-covered

11,000-volt cable. For this particular cable, the insulation over each conductor was 7/32 inch, and the over-all paper wrapping was also 7/32 inch thick.

The rapid increase in force as the current rises is apparent from the following:

Current in 3/0 three-conductor cable	Force per foot of cable
20,000 amperes	208 pounds
40,000 "	832 "
70,000 "	2,550 "
100,000 "	5,200 "

At 20,000 amperes, the disruptive force is comparatively low, but rising in proportion to the square of the current it reaches a value of over one ton per foot at 70,000 amperes and over 2.5 tons at 100,000 amperes.

The busbars, due to the inherently greater spacing than the conductors of a cable, are subject to a much lower disruptive force per unit length, but on the other hand, since they are supported at only frequent intervals rather than continuously, as is a cable, the force on any support may become excessive. For example, with 20-inch triangular spacing, and 100,000 amperes flowing in each bus, the force on one phase is 100 lb. per foot. With supports nine feet apart, the force on any one support becomes nearly one-half a ton.

Forces with Single-Phase Short Circuit

If the short circuit is between only two line wires, instead of all three, then the average force per foot of line, for the same current value per wire as in a three-phase short circuit, is 15.5 per cent greater. This is clear from the following analysis: Referring to Fig. 1, if the short circuit takes place between phases 1 and 3, then the currents in 1 and 3 conductors are equal and

$$f_{1-3} = -kI^2_m \sin^2 \omega t.$$

$$F_0' = \int_0^{\frac{1}{n}} df_{1-3} = -\frac{k\,n}{a\,\omega} I^2_m \int_0^{\frac{1}{n}} \sin^2 \omega t \, d\,(\omega t) = \text{Average force on one conductor—single-phase short circuit}$$

$$= -\frac{k}{a}\ I^2_{r.m.s.}$$

$$\frac{F_0' \text{ (single-phase)}}{F_0 \text{ (three-phase)}} = \frac{-K\,I^2}{a} \times \frac{-2a}{\sqrt{3}\,KI^2}$$

$$F_0' = F_0 \times 1.155 \qquad (2)$$

If the forces in the curves of Figs. 2 and 3 are multiplied by 1.155, they are applicable to cases of single-phase short-circuit currents, also to direct currents. The plane of maximum stress in the cable is no longer *A B*, as indicated in Fig. 1, but the plane *A' B'*, 30 degrees in advance of *A B*, and perpendicular to the line of centers of phase 1 and 3.

It should be emphasized, however, that a system designed to have a maximum r. m. s. short-circuit current of say 70,000 amperes per phase under three-phase short-circuit conditions will have less than 70,000 amperes on single-phase short circuit, in fact, only 86.6 per cent of 70,000 amperes. And the maximum average mechanical force tending to tear the cable apart will likewise be only 86.6 per cent of the three-phase value.

To show the relation between three-phase and single-phase short circuits take

E_{1-0} = voltage from line to neutral in a three-phase system.
E_{1-2} = line voltage.
Z = impedance per phase in short-circuit path.
F = force tending to tear cable apart.

Three-Phase Short Circuit.

$$I_3 = \frac{E_{1-0}}{Z}$$

$$F_3 = -\frac{\sqrt{3}}{2a}\, k \left(\frac{E_{1-0}}{Z}\right)^2$$

Single-Phase Short Circuit.

$$I_1 = \frac{E_{1-2}}{2Z} = \left(\frac{\sqrt{3}}{2}\right)\frac{E_{1-0}}{Z} = 0.866\,\frac{E_{1-0}}{Z}$$

$$F_1 = \frac{-k}{a}\,\frac{3}{4}\left(\frac{E_{1-0}}{Z}\right)^2$$

Hence $$\frac{I_1}{I_3} = \frac{\sqrt{3}}{2}\,\frac{E_{1-0}}{Z}\,\frac{Z}{E_{1-0}}$$

$$I_1 = 0.866\, I_3 \tag{3}$$

$$\frac{F_1}{F_3} = \frac{+k}{a}\,\frac{3}{4}\left(\frac{E_{1-0}}{Z}\right)^2 \times \frac{2a}{\sqrt{3}\,k}\left(\frac{Z}{E_{1-0}}\right)^2$$

$$F_1 = 0.866\, F_3 \tag{4}$$

Thus, if the point of short circuit is fixed in the system, a short circuit between all three phases gives a current and a mechanical force each 15.5 per cent greater than does a single-phase short circuit. But if the point of short circuit is varied in the system so that the numerical value of the r. m. s. current is the same for three-phase as for single-phase short circuit, then the stresses set up in cables and busbar supports will be 15.5 greater for a single-phase than for a three-phase short circuit.

However, if the average stresses in conductors undergoing short circuits are determined for the maximum r.m.s. current obtainable in a three-phase short circuit, then these forces cannot be exceeded for any condition of single-phase short circuit that may occur on that system.

FORCES ON BUSBARS SPACED IN A STRAIGHT LINE

If the busbars all be in the same plane, the average force acting on the top or bottom bar is only 86.6 per cent as great as if the bars were spaced at the vertices of an equilateral triangle. This relation can be shown as follows, using the notation on page 25 and the diagram in Fig. 4.

The force on conductor 1 due to the currents in 2 and 3 equals

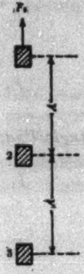

FIG. 4

$$F_3' = \int_0^{\frac{1}{n}} f_{1-2} + f_{1-3}$$

$$f_{1-2} = \frac{k}{A} i_1 i_2$$

$$f_{1-3} = \frac{k}{A} i_1 i_3$$

$$F_3' = \frac{n\ k\ I_m^2}{\omega A} \int_0^{\frac{1}{n}} \left(-\frac{3}{4} \sin^2 \omega t + \frac{\sqrt{3}}{4} \sin \omega t \cos \omega t \right) d\,\omega t$$

$$= -\frac{3}{4} \frac{k\ I^2_{r.m.s.}}{A}$$

$$F_3' = \frac{-4.04\, I^2 \times 10^{-7}}{A} \text{ lb. per foot} \tag{5}$$

(I in r. m. s. amperes—A in inches).
From equation (**1**)

or

$$F_0 = -\frac{4.67\, I^2 \times 10^{-7}}{a}$$ force on conductor at vertex of equilateral triangle.

$$\frac{F_3'}{F_0} = 0.866 \qquad (\mathbf{6})$$

That is, for a given minimum spacing, A, between the nearest two conductors, the straight line arrangement gives only 86.6 per cent of the stress on busbar supports which exists with equilateral triangular spacing.

From equation (**5**), the curves in Fig. 5 are plotted. These are similar to those in Fig. 3, merely being reduced by the factor 0.866, as is indicated in equation (**6**). They represent the force acting on either the top or bottom busbar with the arrangement of buses shown in Fig. 4. This force acts outwardly in both cases that is, in the plane of all three buses and away from bus No. 2.

From the foregoing analysis, it is clear that if mechanical force in the conductors undergoing short circuit is the limiting feature of a system, in three-phase cables this may be controlled by reducing the possible current flow under short circuit by use of reactors; or increasing the size of the cable and thus increase the spacing of the conductors. With busbars, the mechanical forces may also be decreased in the same way as above described for cables, and they may be further reduced by the method of arrangement, that is, by placing the bars in the same plane rather than at the vertices of an equilateral triangle.

HEATING OF CABLES DURING PERIOD OF SHORT CIRCUIT

Typical Short-Circuit Current Waves. When short-circuit conditions occur on an alternating-current power system, the current does not drop into its steady state at once, but rather starts at a given value, depending on the instant of short circuit, and falls off gradually until the induced voltage in the generators has been reduced by armature reaction to that value which will maintain in the short-circuit path the current which will keep the net generator field at the proper value for sustained short-circuit conditions.

Two typical curves of short-circuit current in generators having 10,000 to 30,000 kv-a. rating are shown in Fig. 6. The full line curve placed symmetrically with respect to the zero line is the voltage wave of the machine undergoing short circuit. The dotted symmetrical curve is the short-circuit current, provided the

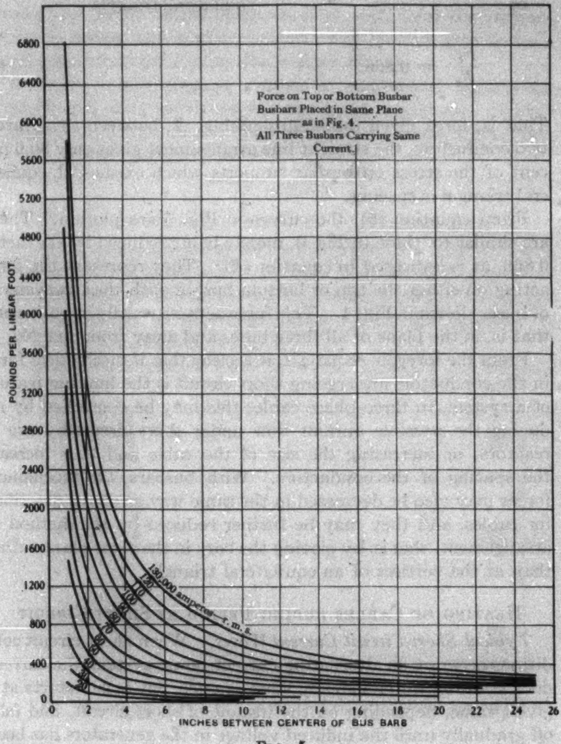

FIG. 5

instant of short circuit occurs at a time when the voltage wave is a maximum or t = 0.02 seconds in Fig. 6. (This assumes only reactance in the short-circuit path).

The assymmetrical current wave in Fig. 6 represents the variation of current if the short circuit takes place at a time $t = 0.01$ second; that is, at a time when the normal voltage is zero. The first peak value of this assymmetrical current wave is nearly twice the first peak value of the symmetrical current wave. But theoretically it can never be exactly twice the symmetrical value, being slightly decreased on account of the falling off of the exponential current and further by the gradually decreasing voltage wave. The curves of Fig. 6 are plotted with arbitrary scales for a 25-cycle circuit, but from the limiting peak values there shown similar curves can readily be drawn for circuits of any frequency, voltage, and current.

The large current rush at the instant of short circuit, taking place at normal generator induced voltage, represents an enormous amount of power, and lasting for several cycles, delivers a considerable amount of energy to the electric conductors undergoing short circuit and there will inevitably result a rise in temperature in the conductors. Since this energy is stored in the conductor in a comparatively short time, one second as an outside limit, it is clear that very little radiation can occur in this brief interval, and consequently the conductor may have its temperature raised to such a point as to injure the cable insulation, or, if the current is great enough, even melt the conductor itself.

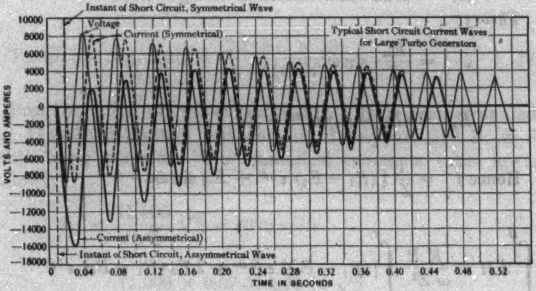

FIG. 6

To determine the heating effect in conductors carrying short-circuit currents of the transient character shown in Fig. 6, the following analysis is given:

First take the symmetrical current wave; that is, the one with its positive and negative waves approximately equal.

Let i = current at any time t.
E_m = peak value of voltage wave at any time.
E_0 = " " " " " under sustained short circuit.
Z = ohms impedance in short circuit path.
ϵ = base of hyperbolic logarithms = 2.718.
β = A constant depending on rate of decrease of generated voltage.
R = ohmic resistance in short circuit path considered
ω = $2 \pi n$
n = frequency in cycles per second.
K = a numerical constant.
H = energy
E_1 = peak value of normal voltage wave.

Theory.

$$i = \frac{E_m}{Z} \sin \omega t.$$

$$E_m = (E_1 - E_0)\, \epsilon^{-\beta t} + E_0$$

Hence $i = \frac{1}{Z} [\, (E_1 - E_0)\, \epsilon^{-\beta t} + E_0] \sin \omega t.$

$$\int_0^H d\,H = \frac{K\,R}{\omega\, Z^2} \int_0^t [\, (E_1 - E_0)^2\, \epsilon^{-2\,\beta t} + 2\, E_0\, (E_1 - E_0)\, \epsilon^{-\beta t} + E_0^2] \sin \omega t\, d\, (\omega t).$$

Integrating

$$H = \frac{K\,R}{\omega\, Z^2} \left[\frac{(E_1 - E_0)^2}{4 + \frac{4\, \beta^2}{\omega^2}} \times \frac{\omega}{\beta} + \frac{4\, E_0\, (E_1 - E_0)}{4 + \frac{\beta^2}{\omega^2}} \frac{\omega}{\beta} \right.$$

$$+ \frac{(E_1 - E_0)^2}{4 + \frac{4\, B^2}{\omega^2}}\, \epsilon^{-2\,\beta t} \left(\sin\, \omega t \left\{ - \frac{2\, B}{\omega} \sin \omega t - 2 \cos \omega t \right\} - \frac{\omega}{\beta} \right)$$

$$+ \frac{2\, E_0\, (E_1 - E_0)}{4 + \frac{\beta_2}{\omega_2}}\, \epsilon^{-\beta t} \left(\sin\, \omega t \left\{ - \frac{\beta}{\omega} \sin\, \omega t - 2 \cos\, \omega t \right\} - \frac{2\omega}{\beta} \right)$$

$$\left. + E_0^2 \left(\frac{\omega t}{2} - \frac{1}{4} \sin 2\, \omega t \right) \right]$$

or $H = \frac{C K R}{\omega Z^2}$ where C equals the above expression in brackets.

$= \frac{C R}{\omega Z^2}$ watt-seconds. (t in seconds, E in volts, R in ohms, and Z in ohms)

Take the specific heat of copper as 0.095.

Resistance of copper 11.75 ohms per cir. mil-ft.

1 B. t. u. = 1055 joules.

Weight of copper 3.03×10^{-6} lb. per cir. mil-ft.

Hence deg. fahr. temperature rise

$$= \frac{C}{\omega Z^2} \frac{3.86 \times 10^4}{(C. M.)^2}$$

$$\text{Temp. rise deg. cent.} = \frac{2.143\, C \times 10^4}{\omega Z^2 (C.M.)^2} \tag{7}$$

From equation (7) the curves of Fig. 7 have been computed. An 11,000-volt system was chosen, three-phase 3/0 B. & S. cable being assumed. The numerical constants taken are as follows:

$$E_1 = \frac{11{,}000}{\sqrt{3}} \sqrt{2} = 8970 \text{ volts.}$$

$$E_0 = \frac{11{,}000 \times 0.07 \times 1.75 \times \sqrt{2}}{\sqrt{3}} = 1100 \text{ volts.}$$

In determining E_0 the generators short-circuited are assumed to have 7 per cent inherent reactance and a sustained short-circuit current of $1\frac{3}{4}$ times normal full load current.

cir. mils = 167,800 for 3/0 B. & S. cable.

n = 25 cycles.

β = 2.51 from Fig. 6.

To determine Z, first assume the current for any temperature curve desired, 50,000 amperes, for example. Then the r.m.s. phase voltage $\frac{11{,}000}{\sqrt{3}}$ above, or 6350 volts divided by Z, gives the r. m. s. amperes as indicated in Fig. 7.

Thus $\frac{6350}{Z} = 50{,}000$, or $Z = 0.127$ ohms.

This value of Z is then used in equation (**7**). The curves of Fig. 7 have been computed on the assumption that no radiation of heat has taken place between the instant of short circuit and 0.8 second later, all the energy going into the conductor being transformed into heat and stored in the cable as such.

Assuming that the modern oil switch will clear trouble within 0.18 second (4½ cycles on a 25-cycle circuit) after short circuit, it will be noted that should the short-circuit current reach 40,000 amperes (r.m.s. symmetrical) on the initial rush the temperature in any 3/0 conductors carrying such current would be increased approximately 155 deg. cent. At 45,000 amperes the temperature rise is 195 deg. cent., and at 50,000 amperes 235 deg. cent. The melting point of copper is 1085 deg. cent., so the copper is in no danger of melting if the oil switch operates normally. On the other hand, temperatures as high as 200 deg. cent. may injure the cable insulation and later cause trouble from short circuits and will surely result in decreased life.

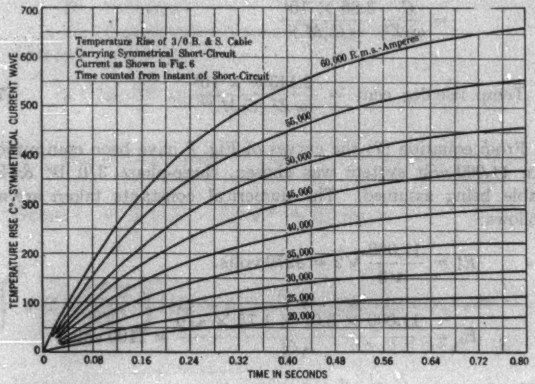

Fig. 7

Heating of Cables Carrying Asymmetrical Current Wave

To determine the heating effect of the asymmetrical current wave, it is merely necessary to follow the same general procedure as described above for the symmetrical wave.

First, obtain the expression for the instantaneous current, then square and integrate and convert to heat units, and then into temperature rise for any given size cable.

The notation is the same as that given under the analysis for heating with a symmetrical current wave, with the following additions. All voltages, currents, and impedances are *per phase* values.

α = a constant depending on the rate of falling off of the asymmetrical current over and above the rate of falling off of the symmetrical wave.

A = a constant depending on the instant of short circuit.

$= \mp \frac{E_1}{Z}$ for maximum displacement of asymmetrical wave, − when the asymmetrical wave is on the negative side of the zero line and + when on the positive side of the zero line.

Theory.

$$E_m = (E_1 - E_0)\,\epsilon^{-\beta\left(t - \frac{\pi}{2\omega}\right)} + E_0.$$

$$i = \frac{E_m}{Z}\sin(\omega t) + A\,\epsilon^{-\alpha\left(t - \frac{\pi}{2\omega}\right)}$$

$$\int_0^H dH = \frac{K R}{\omega}\int_{\pi/2\omega}^{t}\left[\frac{E_m}{Z}\sin wt + A\epsilon^{-\alpha\left(t - \frac{\pi}{2\omega}\right)}\right]^2 d\,\omega t \qquad (8)$$

Hence t_1 the time after the short circuit takes place $= t - \pi/2\omega$. In the above equation t cannot be less than $\pi/2\omega$. Substituting E_m in equation (8), integrating, and substituting limits,

$$\frac{H}{KR} = \frac{1}{\omega}\left(\frac{E_1 - E_0}{Z}\right)^2 \epsilon^{\frac{\beta\pi}{\omega}}\left[\frac{\epsilon^{-2\beta t}}{4 + \frac{4\,\beta^2}{\omega^2}}\left(\sin\omega t\left\{-\frac{2\beta}{\omega}\sin\omega t\right.\right.\right.$$

$$\left.\left.\left.-2\cos\omega t\right\} - \frac{\omega}{\beta}\right) + \frac{\epsilon^{-\frac{\beta\pi}{\omega}}}{4 + \frac{4\,\beta^2}{\omega^2}}\left(\frac{\omega}{\beta} + \frac{2\beta}{\omega}\right)\right]$$

$$+ \frac{1}{\omega}\left(\frac{E_0}{Z}\right)^2\left[-\frac{1}{2}\cos\omega t\sin\omega t + \frac{\omega t}{2} - \frac{\pi}{4}\right] +$$

$$+\frac{2}{\omega}\left(\frac{E_1-E_0}{Z}\right)\frac{E_0}{Z}\epsilon^{+\frac{\beta\pi}{2\omega}}\left[\frac{\epsilon^{-\beta t}}{4+\left(\frac{\beta}{\omega}\right)^2}\left(\sin\omega t\left\{-\frac{\beta}{\omega}\sin\omega t\right.\right.\right.$$

$$\left.\left.\left.-2\cos\omega t\right\}-\frac{2\,\omega}{\beta}\right)+\frac{\epsilon^{-\frac{\beta\,\pi}{2\,\omega}}}{A+\left(\frac{\beta}{\omega}\right)^2}\left(\frac{\beta}{\omega}+\frac{2\,\omega}{\beta}\right)\right]$$

$$-\frac{A^2\,\epsilon^{\frac{\alpha\pi}{\omega}}}{2\,\alpha}\left[\epsilon^{-2\,\alpha\,t}-\epsilon^{-\frac{\alpha\,\pi}{\omega}}\right]$$

$$+\frac{2\,A}{\omega}\left(\frac{E_1-E_0}{Z}\right)\epsilon^{(\alpha+\beta)\frac{\pi}{2\,\omega}}\left[\frac{\epsilon^{-(\alpha+\beta)\,t}\left(-\frac{\alpha+\beta}{\omega}\sin\omega t-\cos\omega t\right.}{1+\left(\frac{\alpha+\beta}{\omega}\right)^2}\right.$$

$$\left.+\frac{\epsilon^{-(\alpha+\beta)\frac{\pi}{2\,\omega}}\left(\frac{\alpha+\beta}{\omega}\right)}{1+\left(\frac{\alpha+\beta}{\omega}\right)^2}\right]$$

$$+\frac{2\,A}{\omega}\,\frac{E_0}{Z}\,\epsilon^{\frac{\alpha\,\pi}{2\,\omega}}\left[\frac{\epsilon^{-\alpha\,t}\left(-\frac{\alpha}{\omega}\sin\omega t-\cos\omega t\right.}{1+\left(\frac{\alpha}{\omega}\right)^2}\right.$$

$$\left.+\,\epsilon^{-\frac{\alpha\,\pi}{2\,\omega}}\left(\frac{\alpha}{\omega}\right)\frac{1}{1+\left(\frac{\alpha}{\omega}\right)^2}\right] \tag{9}$$

Denoting the right-hand side of the equation by $D/Z^2\omega$,

$$H = \frac{K\,R\,D}{\omega\,Z^2}$$

$$= \frac{D\,R}{\omega\,Z^2}$$ watt-seconds. (t in secs., E in volts, R in ohms and Z in ohms.)

As in the symmetrical current wave,

$$\text{temperature rise deg. cent.} = \frac{2.143\, D \times 10^4}{\omega Z^2\ (C.\ M.)^2} \qquad (10)$$

This equation is similar to equation (7) and, in solving, the same circuit constants are used, with the addition of α, which has been determined as 8.65 from the curves of Fig. 6.

From the above equation (**10**) the temperature rise curves of Fig. 8 have been computed, and marked "r.m.s. amperes." To avoid any ambiguity as to the meaning of the term r.m.s. amperes as applied to the asymmetrical wave of Fig. 6, take the following example. Let a three-phase, 11,000-volt generator be short-circuited across its own terminals. The phase voltage will be $11{,}000/\sqrt{3} = 6350$ volts. Let the impedance of the machine be 0.127 ohms per phase. Then the r.m.s. short-circuit current is 6350/0.127, or 50,000 r.m.s. amperes. Any 3/0 conductor carrying this current will have its temperature in-

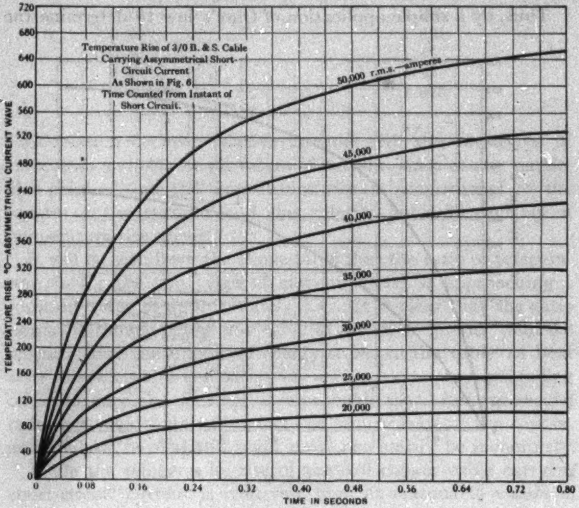

FIG. 8

creased according to the temperature rise curve marked " 50,000 r. m. s. amperes " in Fig. 7, if the wave is symmetrically placed about the zero axis as the dotted curve in Fig. 6.

If the short circuit takes place at such a point of the voltage wave that the current is almost totally displaced one side of the zero line as the full line current curve of Fig. 6, then the heating of 3/0 conductor carrying the 50,000 r.m.s. amperes asymmetrical as above indicated, will follow the temperature rise curve marked " 50,000 r. m. s. amperes " in Fig. 8.

Thus, by a simple application of Ohm's law to determine the r.m.s. current, the heating of a 3/0 conductor with either the symmetrical or asymmetrical current wave, can be determined from Figs. 7 and 8 respectively. The curves in these last two figures apply only to 3/0 B. & S. cable, and currents which decrease in accordance with the current waves of Fig. 6. However, by the use of equations (**7**) and (**10**) the heating produced by any symmetrical or asymmetrical current waves and for any size cable may be determined.

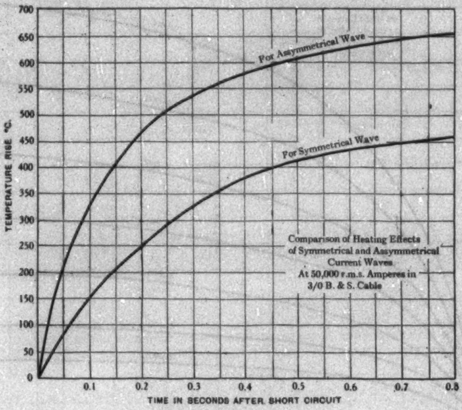

Fig. 9

To compare the heating effect of the symmetrical and asymmetrical current waves for the same r.m.s. current, the two curves of Fig. 9 have been plotted. These curves represent the temperature rise for 50,000 amperes r.m.s. in 3/0 B. & S. cable. It will be observed that the heating due to the asymmetrical current is very much in excess of that due to the symmetrical wave. For example, in this case the relative heating with the same r.m.s. current is as follows:

Sec. after short-circuit	$\frac{\text{Asymmetrical Current Temp. Rise}}{\text{Symmetrical Current Temp. Rise.}}$
0.05	2.47
0.10	2.20
0.20	1.825
0.40	1.52
0.60	1.46
0.80	1.425

This relation between relative heating with the two types of current waves holds for all values of current, since at any particular point of time the temperature rise is proportional to the square of the current, and this relation holds for each set of temperature rise curves.

It will be seen from the above table that the ratio of temperature rise for the two types of current curves is approaching a constant value of approximately 1.4. It is clear that the ratio cannot fall much below this value at any time greater than 0.8 second, since the amount of energy stored in the cable as heat after this interval is comparatively small, due to the rapid falling off of the current. Further, it is probable that after one second radiation would materially affect the temperature of the copper, and analysis beyond this point must necessarily be incomplete.

While the temperature rise of the 3/0 copper cable carrying short-circuit current is relatively high at reasonable values of current (465 deg. cent. at 50,000 amperes asymmetrical, and 250 deg. cent. for the same symmetrical current at the end of 0.18 sec.), there is still a means of materially and effectively reducing these temperatures in any new system, if possible temperature rise is the limiting feature of the high-tension power circuit. This is by increasing the normal kilovolt-ampere rating of the underground cables.

Referring to equations (**7**) and (**10**), it will be observed that the temperature rise is inversely proportional to the square of the circular mils of copper, that is, to the square of the cross-section of the conductor in which the short-circuit current flows. Thus, if the cross-section of the conductor is doubled, the temperature rise is only one-quarter as great. From the relation between temperature rise and conductor cross-section given in equations (7) and (10), and the temperature rise curves of Figs. 7 and 8, the curves of Figs. 10, 11, 12 and 13 have been computed. These

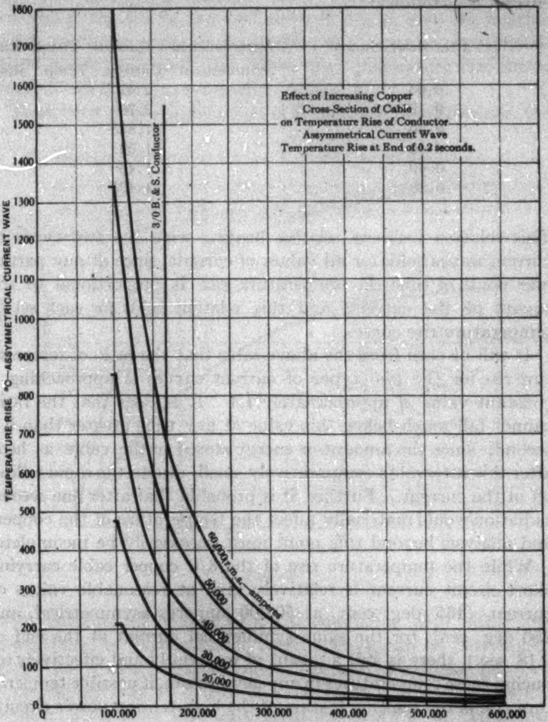

FIG. 10

show graphically the rapid decrease of temperature rise of the copper carrying short-circuit current as the cross-section of the conductor is increased. Figs. 10 and 11 represent temperature rise for various size conductors at the end of 0.2 and 0.5 second respectively, when carrying an asymmetrical current wave as shown in Fig. 6. In Figs. 12 and 13 are shown similar curves for the symmetrical current wave of Fig. 6.

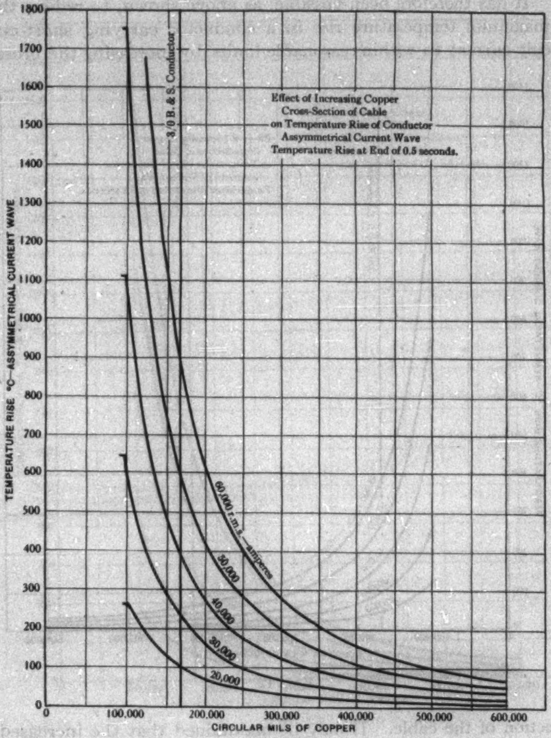

FIG. 11

For illustration, take the temperature rise curves of Fig. 10, computed for an asymmetrical current of 50,000 amperes. If 3/0 B. & S. conductor carries the short-circuit current, its temperature will be raised 480 deg. cent. in 0.2 second. If the conductor has a cross-section of 250,000 cir. mils the temperature rise will be only 217 deg. cent., and if it has 300,000 cir. mils cross-section, the rise will be still further reduced to 150 deg. cent. in the same time.

It has therefore been possible, as above shown, to reduce the maximum temperature rise in a conductor carrying short-circuit current to within reasonable limits, by increasing the cross-section of the cable. It may be maintained that the increased size of cable will reduce the total impedance in the short-circuit path and a larger current will flow than when using a smaller size cable. It should be borne in mind, however, that the maximum short-circuit current will obviously exist in a power system when the short circuit is nearest the power house, and the additional cable length in the short-circuit path, assuming the trouble to

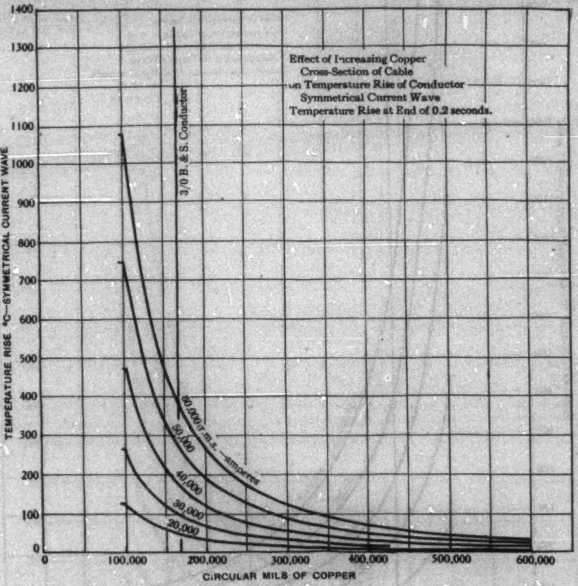

FIG. 12

occur at a short distance from the power house, will merely reduce the current below the maximum value which could exist if the short circuit took place at the power house.

For example, if a given power system has a maximum short-circuit current output of 50,000 amperes, with the short circuit occurring just outside the feeder oil switch at the power house, any other location of trouble on that feeder will necessarily give a current smaller than 50,000 amperes; and this is true independent of the size of the feeders. If the short circuit should occur several miles from the power house the impedance of the cable

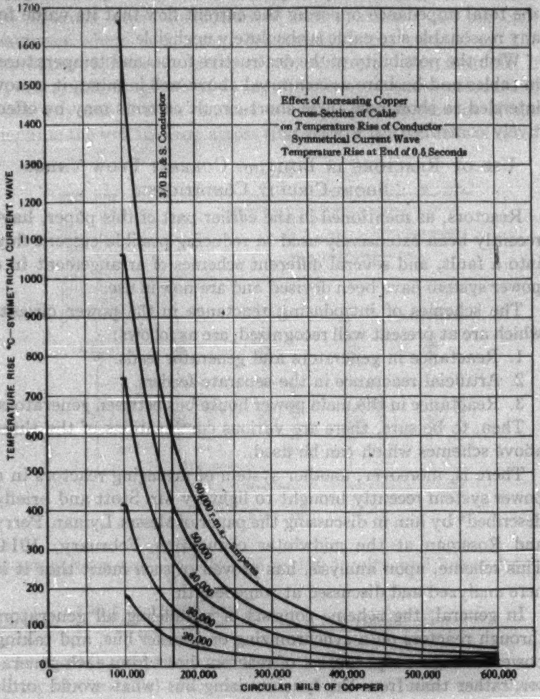

FIG. 13

would materially reduce the current below 50,000 amperes, and the smaller the cable the greater would be this reduction.

For cases of short circuit close to a power house using reactors to limit its abnormal current flow, the impedance of that part of the cable in the short-circuit path is such a small percentage of the total impedance opposing the current flow that its value for any reasonable size cable is absolutely negligible.

With the possibility of the destructive forces and temperatures in cables and busbars as computed above well in mind, it is now intended to show how these short-circuit currents may be effectively controlled.

USE OF REACTORS IN LIMITING CURRENT FLOW UNDER SHORT-CIRCUIT CONDITIONS

Reactors, as mentioned in the earlier part of this paper, have recently been extensively used in reducing possible current flow into a fault, and several different schemes of arrangement in a power system have been devised and are now in use.

The schemes of introducing reactance in the power circuits which are at present well recognized, are as follows:

1. Reactance in generators and generator leads.
2. Artificial reactance in the separate feeders.
3. Reactance in the main power house bus between generators.

Then, to be sure, there are various combinations of the three above schemes which can be used.

There is, moreover, another system of arranging reactors in a power system recently brought to light by Mr. Stott and briefly described* by him in discussing the paper of Messrs. Lyman, Perry and Rossman at the midwinter convention, February, 1914. This scheme, upon analysis, has proved of such merit that it is here analyzed and discussed at some length.

In general, the scheme consists of paralleling all generators through reactors on a synchronizing or transfer bus, and taking power through a separate set of reactors direct from each generator, rather than from the synchronizing bus (what would ordinarily be the main station bus). The scheme is shown diagrammatically in Fig. 14. For convenience of reference, Z_G is called the generator reactance, either inherent, or inherent plus external. Z_X is called the synchronizing reactance, being placed partly for synchronizing purposes but more especially to limit abnormal current flow, and Z_B is called the feeder bus reactance, being in the path of direct feed from the generator to the feeder bus.

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*TRANS. A.I.E.E., 1914, Vol. XXXIII, Part I, page 47.

For purposes of analysis, a power house with an installed capacity of 180,000 kv-a. in 30,000-kv-a. generators, that is, six machines, only five being used at any one time, is taken. Also a system with a nominal voltage of 11,000 volts is used in determining current flow, and 3/0 three-conductor 3217-kv-a. cables are assumed where considered in computations. All per cent reactance where used, except feeder reactance, is based on the maximum 30,000 kv-a. rating of one machine. For example, if Z_B, Z_G, or Z_X is spoken of as say 3 per cent, it is understood that when any one of these reactors is carrying rated current of one machine the voltage drop across that reactor is 3 per cent of rated phase voltage, or $\frac{11,000}{\sqrt{3}} \times 0.03 = 190.5$ volts, and has a reactance of $\frac{190.5 \times 11,000 \times \sqrt{3}}{30,000,000} = 0.121$ ohms.

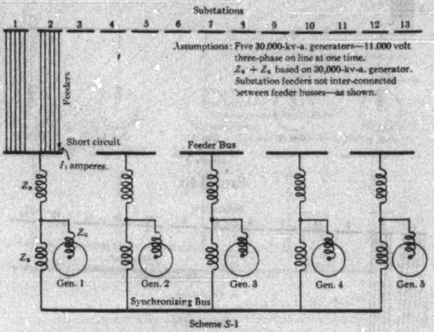

Substations
1
2
3
4
5
6
7
8
9
10
11
12
13
Assumptions: Five 30,000-kv-a. generators—11,000 volt three-phase on line at one time.
$Z_B + Z_X$ based on 30,000-kv-a. generator.
Substation feeders not inter-connected between feeder busses—as shown.
Feeders
Short circuit
I_1 amperes.
Feeder Bus
Z_B
Z_G
Z_X
Gen. 1
Gen. 2
Gen. 3
Gen. 4
Gen. 5
Synchronizing Bus
Scheme S-1

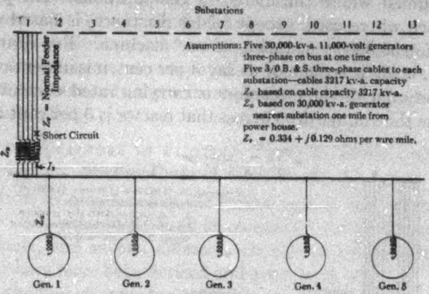
FIG. 14

In speaking of feeder reactance, its value is based on the kv-a. rating of the cable. For example, a 5 per cent feeder reactance, the feeder being rated at 3217 kv-a., has a voltage drop of $(11,000/\sqrt{3}) \times 0.05 = 317.5$ volts and a reactance of

$$\frac{317.5 \times 11,000 \times \sqrt{3}}{3,217,000} = 1.878 \text{ ohms.}$$

DETERMINATION OF SHORT-CIRCUIT CURRENT

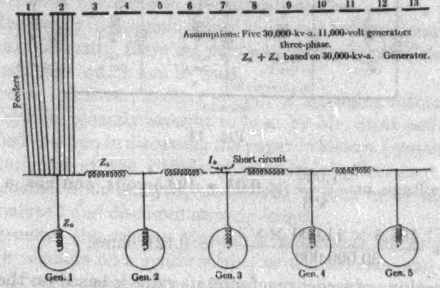
In determining the short-circuit currents in the various networks presented, the following equations were used. All equations are vector equations, but where the resistance involved is negligibly small in comparison to the reactance, the equation may be solved algebraically and the resistance values ignored. This cannot be done in scheme *S*-2, and here the equation for the short-circuit current must be solved vectorially.


Substations
1
2
3
4
5
6
7
8
9
10
11
12
13
Z_F = Normal Feeder Impedance
Short Circuit
Z_G
I_1
Z_G
Gen. 1
Gen. 2
Gen. 3
Gen. 4
Gen. 5

Assumptions: Five 30,000-kv-a. 11,000-volt generators three-phase on bus at one time
Five 3/0 B. & S. three-phase cables to each substation—cables 3217 kv-a. capacity
Z_B based on cable capacity 3217 kv-a.
Z_G based on 30,000 kv-a. generator nearest substation one mile from power house.
$Z_F = 0.334 + j\,0.129$ ohms per wire mile.

Scheme *F*

FIG. 14b.


Substations
1
2
3
4
5
6
7
8
9
10
11
12
13
Feeders
Z_K
I_2
Short circuit
Z_G
Gen. 1
Gen. 2
Gen. 3
Gen. 4
Gen. 5

Assumptions: Five 30,000-kv-a. 11,000-volt generators three-phase.
$Z_G + Z_K$ based on 30,000-kv-a. Generator.

Scheme *B*

FIG. 14c.

The ratio of reactance to resistance in all reactance coils and in the generator itself has been taken as 21.5 where it was necessary to use the resistance values.

Scheme S-1. *Fig.* 14.

$$I_1 = \frac{E}{Z_G + Z_B - \dfrac{4\,Z_G^{\,2}}{5\,(Z_K + Z_G)}} \qquad (15)$$

Scheme F. Fig. 14*b*. Feeders open at substation end

$$I_F = \frac{E_G}{Z_D + \frac{Z_G}{5}} \tag{16}$$

Scheme F. Fig. 14 *b*. Feeders paralleled at substation end

$$I_F = \frac{E}{Z_G\left(\frac{Z_D + Z_F}{Z_D + 5\,Z_F}\right) + Z_D} \tag{17}$$

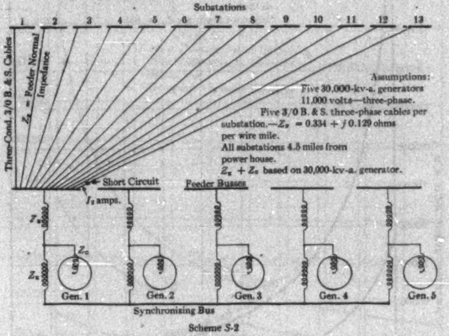

Substations
1
2
3
4
5
6
7
8
9
10
11
12
13
Three-Cond. 3/0 B. & S. Cables
Z_F = Feeder Normal Impedance
Assumptions:
Five 30,000-kv-a. generators
11,000 volts—three-phase.
Five 3/0 B. & S. three-phase cables per substation.—Z_F = 0.334 + j 0.129 ohms per wire mile.
All substations 4.5 miles from power house.
$Z_K + Z_G$ based on 30,000-kv-a. generator.
Short Circuit
I_2 amps.
Feeder Busses
Z_B
Z_G
Z_K
Gen. 1
Gen. 2
Gen. 3
Gen. 4
Gen. 5
Synchronising Bus
Scheme S-2

FIG. 14a.

Scheme B. Fig. 14*c*.

$$I_B = \frac{E\,(5\,Z_G{}^2 + 5Z_G Z_S + Z_S{}^2)}{Z_G{}^3 + 3Z_S\;Z_G^2 + Z_S{}^2\,Z} \tag{18}$$

Scheme S-2. *Fig.* 14*a*. Thirteen substations—5 feeders per substation

$$\begin{aligned} I_2 = E\left(5 + \frac{5\,Z_K}{Z_G}\right)&\left[\frac{305}{48}Z_B + z_K\left(\frac{305}{48} + \frac{305}{48}\frac{Z_B}{Z_G}\right)\right. \\ &\left. + \frac{25}{48}Z_F\left(1 + \frac{Z_K}{Z_G}\right)\right] - \frac{13}{12}Z_G{}^2 + \left[Z_G + Z_K\left(5 + 5\,\frac{Z_B}{Z_G}\right)\right. \\ &\left. + 5Z_B\right]\left[\frac{13}{12}Z_G + \frac{65}{48}Z_K\left(1 + \frac{Z_B}{Z_G}\right)\right. \\ &\left. + \frac{65}{48}Z_B + \frac{25}{48}Z_F\left(1 + \frac{Z_K}{Z_G}\right)\right] \end{aligned} \tag{19}$$

E = generator phase voltage (line to neutral.)

Z = impedance

Equations (**17**) and (**19**) must be solved vectorially; as above noted, the others may be solved, without loss of accuracy, algebraically, if the resistance r of any reactor having an impedance $r + j\,x = Z$, is small in comparison to the reactance x. This is true, in general, for reactors, that is, r/x is negligibly small.

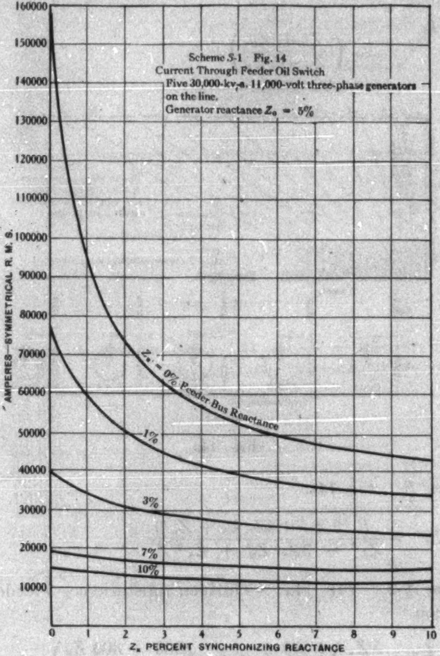


FIG. 15

The above equations were determined for the several cases by the simple application of Ohm's law applied to alternating-current circuits.

From equation (**15**) the short-circuit current curves of Figs. 15 to 21 inclusive have been calculated. Figs. 15 to 19 inclusive show the effect of varying the feeder bus and synchronizing reactance Z_B and Z_X respectively, as the reactance of the machine varies from 5 to 25 per cent, inclusive.

For example, with the 150,000-kv-a. running capacity assumed, suppose it is desired to limit the short-circuit current to 30,000 amperes, the generators having an inherent reactance of 5 per cent. From Fig. 15, it is clear that this may be done by a variety

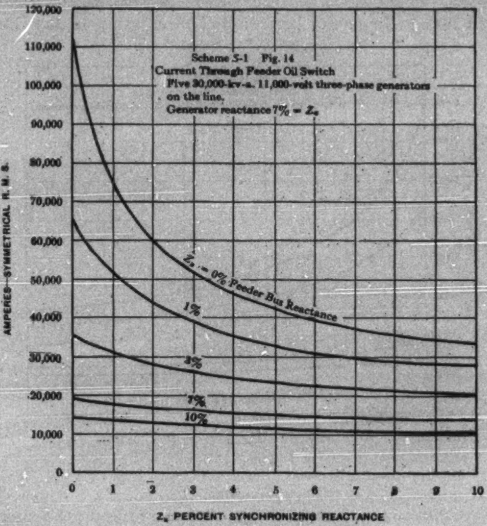


FIG. 16

of combinations of feeder bus reactance and synchronizing reactance, approximately as follows:

Short-circuit amperes	% Z_B	% Z_X	Total % Z
30,000	4.3	0	4.3
30,000	3.0	2.5	5.5
30,000	2.5	5.0	7.5
30,000	2.0	8.0	10.0
30,000	1.6	10.0	11.6

The total Z above is exclusive of the generator reactance. Similar examples can be taken for the curves of Figs. 16 to 19 inclusive, if desired. From the above table it is clear that for a given short-circuit current, when the trouble occurs on the feeder bus, the least reactance is required when that reactance is placed between the feeder bus and the generator, that is, in Z_B. This could have been easily foreseen, since it is clear that with a given reactance in use, the larger the amount in the path of the total current, the smaller will be that current.

It is further obvious from the curves of Figs. 15 to 19 inclusive that the larger the feeder bus reactance, Z_B, the smaller the effect of the synchronizing reactance in further reducing the short-circuit current. This is brought out by the curves in Figs. 15 to 19, where $Z_B = 10$ per cent. For example, in Fig. 15, with generators having 5 per cent reactance and the feeder bus reactance 10 per cent, the short-circuit current only decreases from 14,000 to 11,500 amperes as the synchronizing reactance increases from zero to 10 per cent.

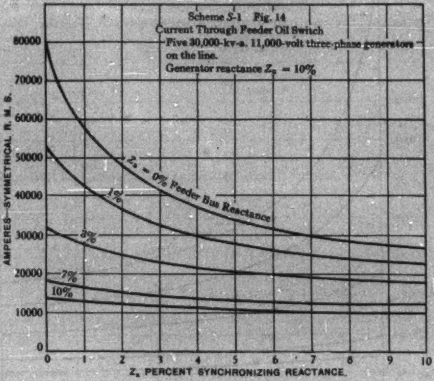


FIG. 17

When the feeder bus reactance is low the synchronizing reactance is useful in reducing the current in short circuits which occur outside the feeder oil switch. But when the feeder bus reactance reaches 5 per cent or greater, the effectiveness of Z_K

in further reducing current flow becomes practically nil. This statement is clearly borne out by a study of curves of Figs. 15 to 19 inclusive and also in Figs. 20 and 21. Still using scheme *S*-1, the curves of Figs. 20 and 21 have been plotted from equation (**15**) (the dotted curves have been plotted from the following

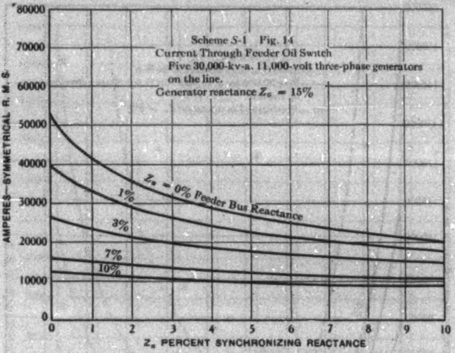


FIG. 18

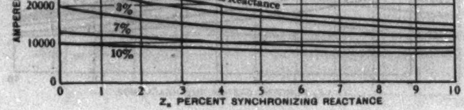


FIG. 19

equations: Fig. 20, amperes = E/Z_B, and Fig. 21, amperes = $E/Z_G + E/Z_K$).

LIMITING EFFECTIVE VALUE OF Z_B

It is here shown in Fig. 20 that if the synchronizing reactance is not used the feeder bus reactance loses rapidly in effectiveness after 5 per cent is reached. The dotted curve represents conditions with an infinite generator capacity on the line and no synchronizing reactance Z_K used. The generators for this curve may have any reactance whatsoever.

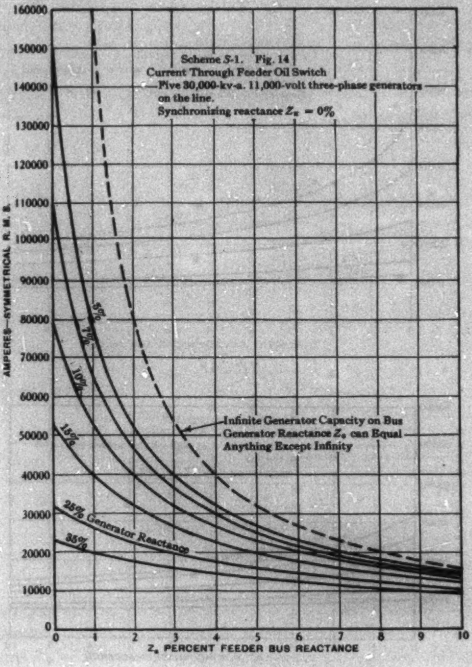


FIG. 20

LIMITING EFFECTIVE VALUE OF Z_K

From Fig. 21, it is clear that the effectiveness of Z_K in reducing currents from short circuit beyond the feeder oil switch falls off rapidly after a value of 3 per cent is reached, and for comparatively large reactance in the generator, an increase above 1 per cent in Z_K is practically useless.

The dotted curve of Fig. 21 shows the limiting value of short-circuit current when there is an infinite generator capacity on the bus and all generators have 5 per cent reactance. If the generator reactance were higher the limiting curve would be lower. The curves of Fig. 21 assume Z_B equal to zero.

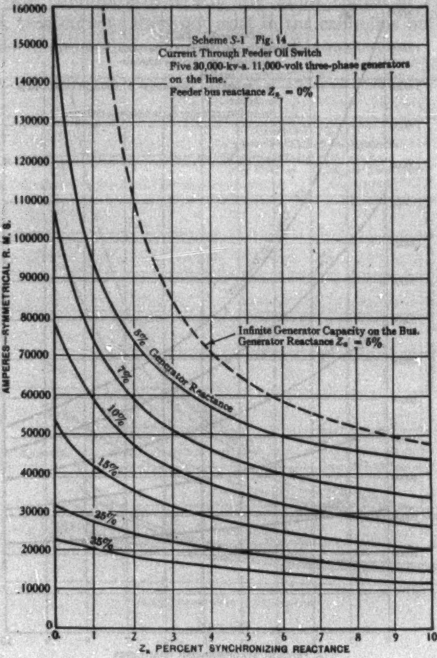


FIG. 21

The use of the synchronizing reactance would at first seem somewhat superfluous when the feeder bus reactance is used, but it is located not only to reduce the current in a short circuit which occurs at the power house beyond the feeder oil switch but also to reduce the current should the short circuit occur on the synchronizing bus, and further to limit the current flow in the event of poor synchronizing.

The effectiveness of Z_K in reducing the maximum current flow when the fault occurs on the synchronizing bus is shown graphically in Fig. 22. With Z_K = 3 per cent and generators having

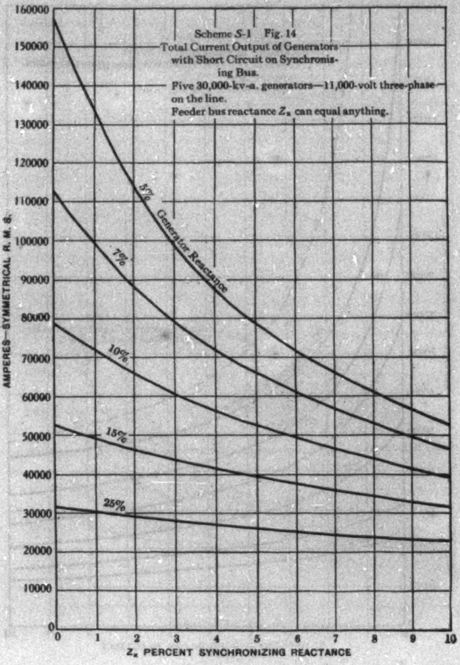


FIG. 22

5 per cent reactance, the current is reduced from 157,500 to 99,000 amperes. Machines having 7 per cent reactance have a current reduction from 112,500 to 79,000 amperes. With the 5 per cent reactance machines there has been a 37 per cent current reduction; with the 7 per cent reactance generators, a 30

per cent reduction, by the use of the 3 per cent synchronizing reactance.

While the currents shown in Fig. 22 are comparatively large, it should be observed that these currents cannot exist in any one conductor, since they represent the total instantaneous output of the five machines. Thus the largest current which can exist in any one conductor is 4/5 of the values shown in Fig. 22. Further, this current does not exist in the cable line but circulates only in the machine and synchronizing bus circuit.

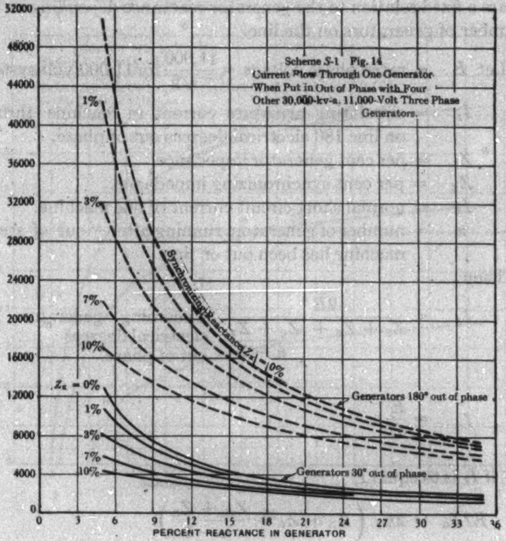


FIG. 23

POOR SYNCHRONIZING

As mentioned earlier in this paper, the purpose of Z_K, the synchronizing reactance, is partly to furnish protection against short circuits on the system and partly to be of aid in limiting current in times of poor synchronizing. If four machines should be running and the fifth then put on the line 180 electrical degrees out of phase, the upcoming machine would have circulating in its windings a current considerably in excess of its maximum short-circuit current, provided no synchronizing reactance Z_{K} were used. The effectiveness of Z_{K} in reducing this current is shown graphically in Fig. 23 for various values of generator reactance, when one machine is thrown on the line both 180 electrical degrees out of phase (dotted curves) and also for 30 degrees (full line curves).

Should it be desired to raise the value of Z_{K} so that the maximum current which can flow in any generator thrown on the line 180 degrees out of phase is equal to the normal short-circuit current of one machine, it can be shown that the value of Z_{K} bears a fixed relation to the generator reactance depending on the number of generators on the line.

Let E = rated phase voltage $= \frac{11{,}000}{\sqrt{3}}$ for 11,000-volt system.

I_{z} = circulating armature current in machine thrown on line 180 electrical degrees out of phase.

Z_{G} = per cent generator impedance.

Z_{K} = per cent synchronizing impedance.

I_{s} = normal short-circuit current of one machine.

n = number of generators running after " out of step " machine has been put on line.

Then

$$I_{\mathrm{z}} = \frac{2E}{Z_{\mathrm{G}} + Z_{\mathrm{K}} + \dfrac{Z_{\mathrm{G}} + Z_{\mathrm{K}}}{n-1}}$$

Upcoming generator 180 electrical degrees out of phase.

$$I_{\mathrm{s}} = \frac{E}{Z_{\mathrm{G}}}$$

Or, if I_{z} is to equal I_{s},

$$E/Z_{\mathrm{G}} = 2E/\left(Z_{\mathrm{G}} + Z_{\mathrm{K}} + \frac{Z_{\mathrm{G}} + Z_{\mathrm{K}}}{n-1}\right)$$

Simplifying

$$Z_{\mathrm{K}} = \frac{n-2}{n} Z_{\mathrm{G}} \tag{12}$$

In this equation n obviously cannot be less than 2.

For 120 electrical degrees between upcoming machine and line voltages

$$Z_{\mathrm{K}} = \frac{0.732\,n - 1.732}{n} Z_{\mathrm{G}} \tag{13}$$

and for 90 deg. phase displacement

$$Z_K = \left(\frac{0.414\,n - 1.414}{n}\right) Z_G \qquad (14)$$

From equations (**12**), (**13**) and (**14**) the curves of Fig. **24** are drawn. These curves show the relation between the value of Z_K and Z_G for a different number of machines running. Clearly this relation is independent of the kilovolt-ampere rating of the machine or its per cent reactance.

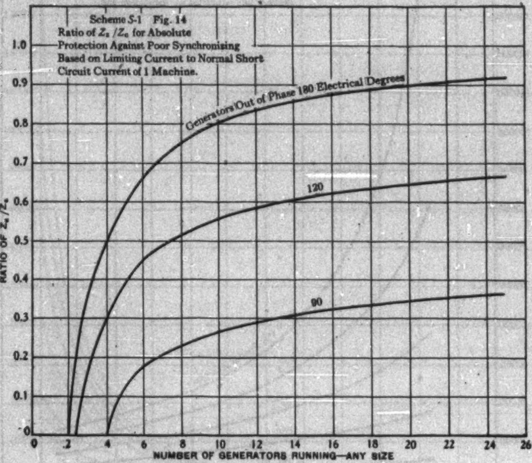


FIG. 24

With a small number of machines running, five for example, Z_K need not exceed 0.6 Z_G for protection of generators against mechanical injury due to the worst possible conditions of poor synchronizing. Thus with generators having 7 per cent inherent reactance the synchronizing reactance need not exceed 4.2 per cent for absolute protection to the generators. This assumes, of course, that any machine may safely withstand dead short circuit at its own terminals.

It is of interest to note that the lower the inherent reactance of the generators the lower will be the value of Z_K, and for purposes of easy distribution of load between the several generators when the load decreases and one or more generators are taken off the line, a low value of Z_K will cause either the voltage on the feeder bus now not fed directly by a generator to fall, or the power factor of the load taken from this feeder bus to be changed. For the best distribution of load and the most nearly constant value of voltage at different feeder buses, the lower Z_K is, the better.

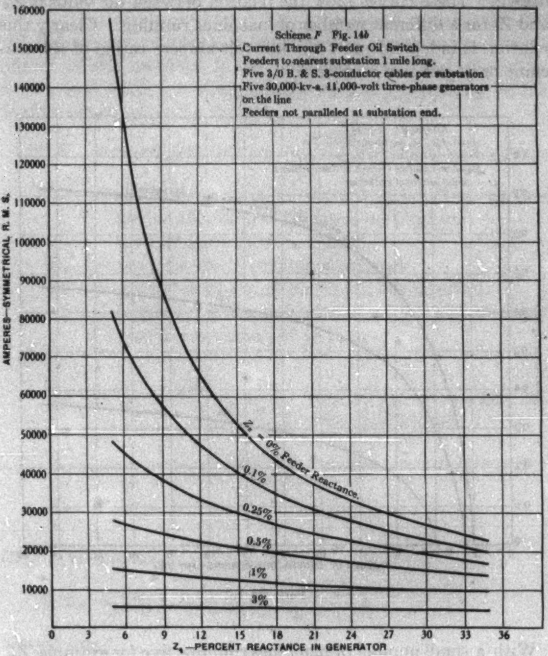


FIG. 25

To compare this scheme, S-1, of using feeder bus reactances and synchronizing reactance, with feeder reactance, scheme F, shown in Fig. 14b, and with bus reactance, scheme B, shown in Fig. 14c, the curves of Figs. 25, 26 and 27 have been computed. The same system of five 30,000-kv-a. 11,000-volt generators has been assumed.

From Fig. 26 it is seen that with generators having a 5 per cent reactance, a feeder reactance of 1 and 1.5 per cent reduces the current to values of 15,500 and 10,000 amperes respectively, and further it is clear that nearly the entire drop occurs in the feeder reactance, especially when the generator reactance is low. There are, however, two disadvantages of this scheme:

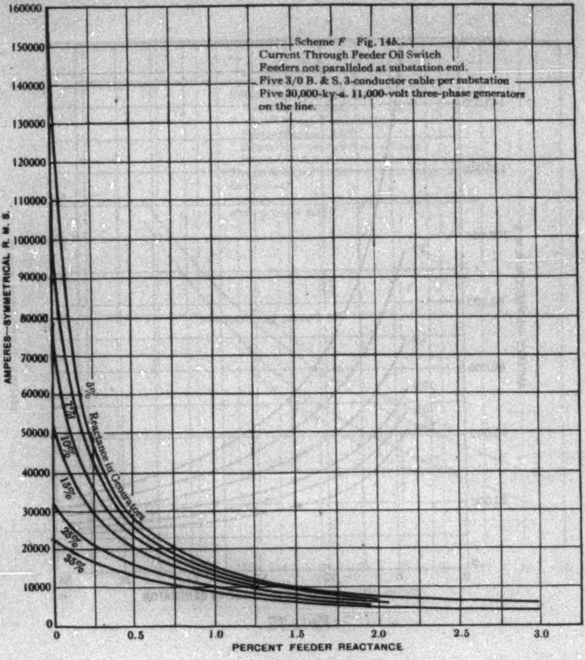


FIG. 26

1. When a short circuit occurs on the bus, the current flow becomes enormous; the bus voltage drops to zero and all synchron-

ous apparatus is certain to drop out of step if the trouble is not instantly cleared.

2. When a machine is put on the line out of phase, there is no means of limiting the current in the synchronizing circuit. (See Fig. 29). Both of these objections may be overcome in scheme *S*-1. The advantage of this scheme *F* is that when trouble occurs outside the feeder oil switch the trouble is localized in the feeder experiencing conditions and may be quietly cleared from the line, without a shock to the entire system.

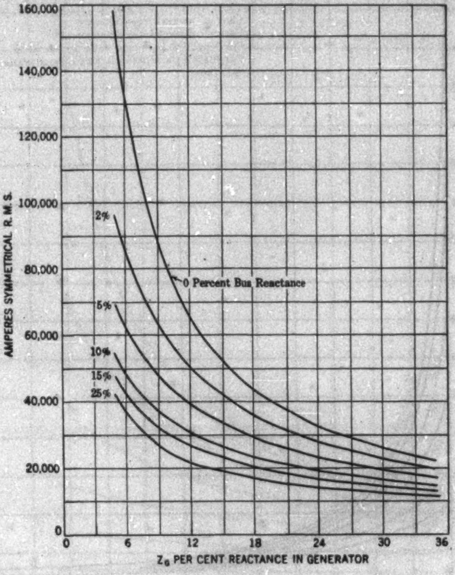


FIG. 27

Bus reactance as shown in scheme *B* is analyzed graphically in Fig. 27. Suppose, for example, it is desired to limit the short-circuit current on a feeder to 25,000 amperes. This can be done in scheme *B* by using generators have 12 per cent reactance, and bus reactances between machines of 25 per cent. In scheme

S-1 this can be accomplished by a generator reactance of 7 per cent, a feeder bus reactance of about 4 per cent and a synchronizing reactance of 2 per cent. Should the trouble occur on the synchronizing bus in scheme *S*-1, the current would rise to 87,500 amperes (Fig. 22); but this current would not pass through any one oil switch or small cross-section cable. The maximum current obtainable by the use of bus reactance would in this case be 25,000 amperes. Thus, the busbar reactance scheme reduces the short-circuit current to a low value, but at the expense of a large reactance in the circuit.

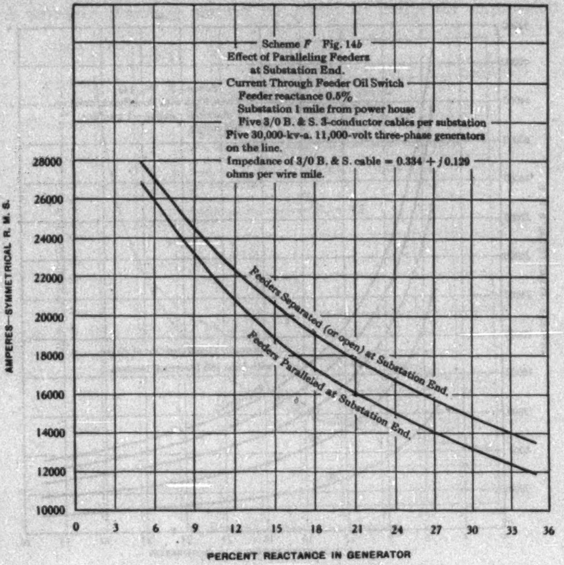


FIG. 28

Another disadvantage of busbar reactance is that under certain conditions of operation it would be necessary to feed through four of the bus reactances, thus producing considerable difference of voltage along the bus. Scheme *S*-1 with its 7, 4 and 2 per cent reactance would be little affected by drop in voltage from one feeder bus to another.

EFFECT OF PARALLELING FEEDERS AT THE SUBSTATION END

In scheme *F*, it is interesting to note (from Fig. 28) that the short-circuit current through the power house feeder oil switch is less when the feeders are paralleled at the substation end than when opened. This at first seems surprising, but on analysis the reason is obvious. The kilovolt-ampere output of the generators is greater when the feeders are paralleled at the substation end, since the path of one feeder reactance in parallel with other circuits to the substation end of the affected feeder and back to the points of short circuit is less than the impedance of one feeder reactance alone. Therefore the current output of the generators

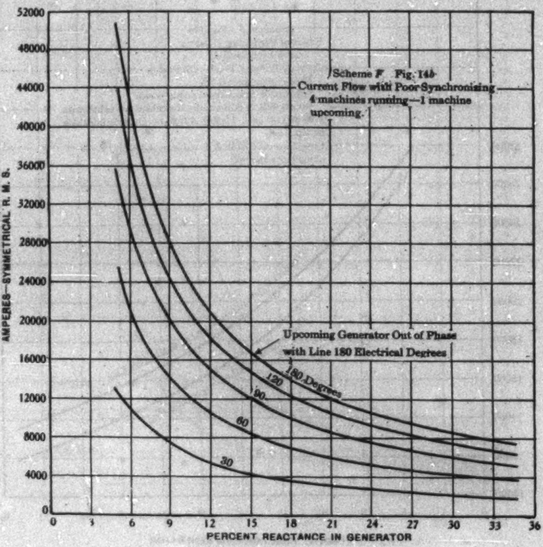


FIG. 29

is greater, and this current flowing through the generator reactance gives a lower bus voltage than when the feeders are not paralleled at the substation. This lower bus voltage impressed across the given feeder reactance therefore produces less current through the feeder oil switch. And if the breaking capacity of the oil switch or heating of the cables is the limiting feature of the system, better results can be obtained by paralleling the feeders at the substation than by leaving them open, in scheme *F*.

A word of warning should be given in using the expression "kilovolt-amperes generated at short circuit;" for, as above shown, the strain on the feeder is less as the kilovolt-amperes generated at instant of short circuit is increased.

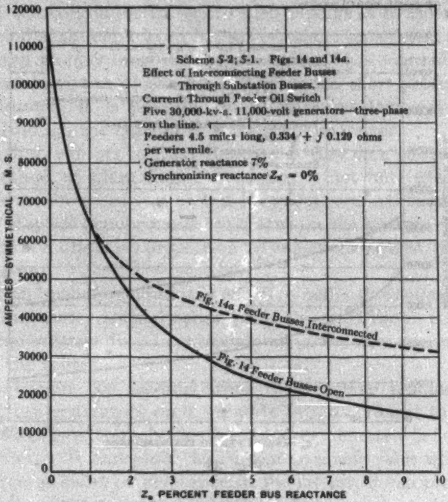


FIG. 30

In scheme *S*-2 great flexibility of operation can be gained by running, to any one substation, feeders from each separate feeder bus. If one bus is now in trouble due to short circuit it is possible by the use of selective relays to clear that feeder bus of feeders, and by this arrangement any substation will lose only one feeder. A substation having five feeders, for example, one to each feeder bus, will lose 20 per cent of its cables, thus imposing 125 per cent load on the remaining cables. In this way service would continue on the system uninterrupted.

Under short-circuit conditions (scheme *S*-2, Fig. 14*a*), however, the current is very much increased, as is shown by the curves of Figs. 30 and 31. It is clear that if it is necessary to limit the short-circuit current in a feeder to 30,000 amperes, it is impossible to interconnect the feeder buses through substation feeders, as in Fig. 14*a*, with any reasonable value of Z_B (machines assumed to have 7 per cent reactance).

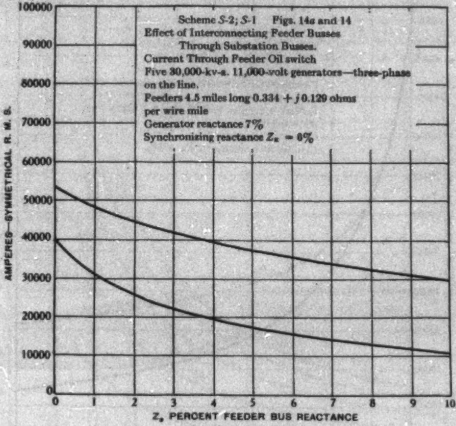


FIG. 31

Another advantage of these schemes *S*-1 and *S*-2, as here presented, is that very low reactance can be used in the generator, in fact as low as mechanical protection to the generator itself justifies. The lower the generator reactance, the higher Z_B can become for a given reactance in the path of direct feed from generator to feeder bus, and the higher will be the bus voltage on the unaffected feeder buses. This results in less possibility of synchronous apparatus dropping out of step at the instant of short circuit.

SUMMARY AND CONCLUSIONS

It has been shown in this paper that the average mechanical forces existing between conductors of a three-phase cable carrying short-circuit currents, and between busbars, rise to relatively high values at the instant of trouble. These forces can be reduced in cables by either limiting the current or increasing the distance between conductors. The same applies to busbars, and in addition, the position of the busbars can be adjusted by placing them in the same plane so that the mechanical forces may be considerably reduced.

The heating of cables may be the limiting feature in controlling short-circuit current, since it is quite possible for the temperature of the conductor to rise to such a point as to endanger the insulation of the cable even in the very short time that it takes an oil switch to operate after the short circuit has occurred. With the characteristics of the generators under short-circuit conditions known, it is possible to compute the temperature rise, even although the current is of transient character.

In using reactors to limit the current flow on a power system, the method of plain feeder reactance is not fully effective, as trouble on the main station bus is almost certain to cause to drop out of step all synchronous apparatus on the system. Further, this method offers no protection to machines against poor synchronizing.

Station busbar reactance is effective under short-circuit conditions, but under normal operation is objectionable on account of the large voltage drop in transmitting power from one end of the bus to the other.

The scheme of feeding from the machine terminals, and paralleling generators on a separate bus, as brought to light by Mr. Stott, is extremely flexible and very effective in furnishing protection. It can limit the current to a safe value without an excessive amount of reactance in the circuit; it can protect the machines against mechanical injury due to poor synchronizing; and can transmit power from between different points of the bus with far less voltage drop than with the bus reactance scheme. It makes possible the use of generators having a low inherent reactance, provided, of course, the machine is designed to withstand dead short circuit at its terminals. Further, the lower the reactance of the generator the less possibility there is of the synchronous apparatus on the system dropping out of step due to reduced power house voltage.

The possibilities of this system are as yet probably not fully realized.

DISCUSSION ON "THEORETICAL INVESTIGATION OF ELECTRIC TRANSMISSION SYSTEMS UNDER SHORT-CIRCUIT CONDITIONS," (GROSS), NEW YORK, JANUARY 8, 1915.

Henry G. Stott: Perhaps a little account of the origin of this paper might be of interest. We were confronted by the problem of providing for a station which would ultimately contain seven 30,000-kw. units, and at the same time trying to avoid the results of six 30,000-kw. units in short circuits. First of all, we were very anxious about protecting the generator from short circuits. After a little investigation of the problem, it became apparent that our efforts should be directed towards the feeders and busbars and not towards the generator, as the generator, with its relatively high reactance and modern construction, seemed to be pretty well able to take care of itself. The problem, then, of saving the feeders from what might happen, as we went further along in the investigation, became rather complex.

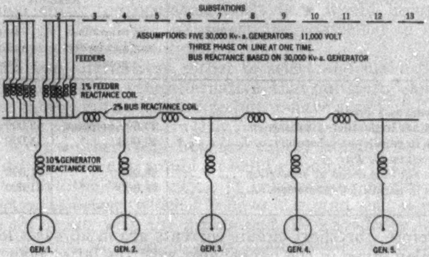
Our first inclination was to insert reactance in each feeder. That seemed to be the logical way, as it placed an absolute limit on the current flowing into a given feeder under any conditions. However, after working over that plan for a little while, it turned out that we would have to build new power stations to hold the reactors, and as property was rather valuable at the place where the station was located, it did not seem practicable to adopt that method, and we abandoned it. We went at the problem from the point of view of inserting reactance in the buses. There we were confronted with the difficulty of enormous drops under certain conditions. If you are operating substations at one end and the generator at the opposite end of the bus, you have enormous reactance drops and losses which would make regulation extremely difficult if not impossible under certain conditions. Then, after considering these various schemes, we stumbled on the one mentioned in the paper, which may be called a split reactance scheme, by which the generator, as you will note, feeds in between two reactances, one of 5 per cent connected directly to the feeder bus and the other of 2 per cent connected to the synchronizing bus.

This matter was thoroughly investigated theoretically by Mr. Gross, and the results were so interesting that I persuaded him to reproduce them in more general fashion in the shape of this paper, as being of general interest to the entire profession, and I think the Institute is to be congratulated upon the very clear method he has pursued.

The rather astonishing things which were brought to light in this investigation were, first, that with five machines on the bus at one time we would get mechanical forces exerted between the conductors in the cables, with the ordinary insulation between them for this voltage, amounting to over one ton per lineal foot. That was alarming in itself, and we then investigated the strength of the outside jacket of insulation, and that was found to be a saving feature. The lead sheath alone would have been ruptured immediately by that force.

Then the next thing, which was really more alarming, was the extremely high temperatures which, with a short circuit of 60,000 amperes, we could cause in the conductors, and which would undoubtedly have destroyed the insulation on the layers next to the copper, as radiation would not enter into the calculation at all during that brief period of probably three to seven cycles.

The next question was: Is it possible to build an oil switch which would rupture 60,000 amperes at 11,000 volts? We consulted with a number of the manufacturers, and while they were all quite confident this could be done, none were exactly anxious to try. We therefore arranged to try to cut it down to about 20,000 amperes, which seemed to be quite conservative when compared to the higher value. With the arrangement of reactances shown we are very hopeful that, under any conditions, we will not get a short circuit exceeding about 22,000 amperes.


SUBSTATIONS
1
2
3
4
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11
12
13
ASSUMPTIONS: FIVE 30,000 Kv-a. GENERATORS 11,000 VOLT
THREE PHASE ON LINE AT ONE TIME.
BUS REACTANCE BASED ON 30,000 Kv-a. GENERATOR
FEEDERS
1% FEEDER REACTANCE COIL
2% BUS REACTANCE COIL
10% GENERATOR REACTANCE COIL
GEN. 1.
GEN. 2.
GEN. 3.
GEN. 4.
GEN. 5.

FIG. 14D

Philip Torchio: We have had, at one time or another, evidences of these great stresses on busbars and switches, and especially on disconnective switches. The latter are now equipped with a special lock, similar to a door lock, which we have found the most successful means for the purpose.

In similar manner, we have had experience with heating of cables, due to short circuits close to the station, resulting in the cable insulation being entirely destroyed. At the time we made some figures about the heating, but this was not necessary, because the evidence was before us.

In reference to Mr. Stott's plan of protective reactors described by Mr. Gross, I wish to point out that, while the plan may be desirable for certain installations, it lacks the flexibility to give the greatest protection where such requirements are considered essential. By substituting individual feeder reactors in place of a reactor for a large group of feeders, with same cost of reactors, the protection could be more than trebled.

To illustrate the point, we might make a comparison between a plan as indicated in Fig. 14 of Mr. Gross's paper, and Fig. 14D, in which I have substituted busbar reactors and individual feeder reactors of equivalent money value, as called for in Mr. Stott's plan of Fig. 14.

Assuming the use of 2 per cent bus reactors in place of 2 per cent synchronizing reactors, and 1 per cent feeder reactors in place of 5 per cent feeder group reactors, we would, in the former case, make an installation of 9000 kv-a. of reactors and in the second case 4500 kv-a. of reactors of approximately equal costs. The protection obtained on the basis of the comparative plans would be as follows:

	Reactors	
	Synchronizing and feeder group	**Bus and individual feeders**
Short Circuit on a Feeder		
Feeders not in parallel at substation	**23,600 amperes**	**12,000 amperes**
Feeders in parallel at substation	**50,000 "**	**13,000 "**
Short Circuit on the Bus		
Feeders not in parallel at substation	**88,000 "**	**76,000 "**
Feeders in parallel at substation	**88,000 "**	**81,000 "**

Therefore, the short-circuit currents are in all cases less than in the plan given in the paper; also, with the latter plan, a short circuit on a feeder affects equally all the other feeders on the section of bus, while in the case of individual feeder reactors, only one feeder is affected. Therefore, with less total kv-a. of reactors installed, greater protection is obtained.

In practise it will be found necessary to secure this greater protection by installing larger reactors than the 1 per cent reactors on feeders and 2 per cent reactors on busbars, assumed in the example for comparison with Messrs. Stott and Gross's example.

In the 201st Street Station of The United Electric Light & Power Company, to which I referred in my discussion* of three months ago of Messrs. Lyman, Perry and Rossman's paper, an illustration was given of 3½ per cent feeder reactors. These reactors were installed in such a confined space as that available under the floor space occupied by a type H or type C oil switch. I emphasize this point as it disposes of the objection that the space requirements may make the use of feeder reactors prohibitive.

During the first applications of reactors, there have been fears

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that the reactors might create trouble by resonance, or surges, but experience has indicated that these fears were unfounded, and the systems have been free from complications of this kind.

The problem of protective reactors for central stations is timely and of great importance. We engineers ought to come to some definite conclusions. We ought to give confidence to the executives of the companies and the people who have to spend the money for this protection, that we are recommending something that will prove satisfactory and will give the results we expect.

We have had a great deal of discussion on this subject, and the same discussion is going on abroad, covering the ground we have gone over here in former years. Now, I think it behooves us to start in and set up some definite standard and demonstrate that our methods of centralization of power supply bring safety as well as economy and efficiency. These items are perhaps of greater importance in this country than would probably be the case abroad, because with high wages and other high costs, the operating costs here would become excessively high should we, for safety, be compelled to operate a multiplicity of small stations.

We had two alternatives, either to select and make the centralized system safe, or the alternative, that our European brethren have taken, not to centralize but to have a system like that in Berlin, for instance, where they run different stations independently, never tie them together, and supply substations isolated so that if they have any trouble it will be confined to one district and not affect the whole city. It behooves us to prove that our selection is better, which I believe it is, and that it is safer, because we ought, with the means and the knowledge we have now, to be able to make it safer than would be an isolated distribution as used abroad.

I do not want to detract from the importance of this paper, because it is very valuable, and I believe that in special situations the arrangement of Messrs. Stott and Gross is a very good one and probably would fill the situation very excellently, but there are other situations where one must go considerably further, and with this scheme I have described, one can get greater protection, and of any degree which one desires.

Cassius M. Davis: Mr. Gross has discussed certain arrangements of feeders, buses and generators, and has worked these several arrangements out in detail and with accuracy. I want to point out two things, one with regard to accuracy and the other with regard to the work which has to be done preliminary to that Mr. Gross describes, namely, trying to find out what is the best arrangement to give the protection desired.

In figuring problems of this kind, one is startled at the amount of inaccurate information which is available to begin with. For example, the generator reactance is not known with accuracy. We have estimates of it, but these estimates are based on assumptions. The generator reactance, then, is more or less unknown. The rate at which the short-circuit current of a generator dies down is more or less unknown. We have then to assume a value of generator reactance and a value for the dying down of the current. We have to assume that we have an absolutely dead metallic short circuit, which is almost never the case. We have to assume, also, for the sake of simplicity in calculations, that in a polyphase short circuit all phases are short-circuited at exactly the same instant, which seldom if ever occurs. We have to assume what the back feed is from the synchronous apparatus in the substations. This point was only briefly touched upon by Mr. Gross, but the back feed from synchronous apparatus in substations forms a very important part of the total short-circuited kv-a. which a switch or feeder may be called upon to carry. We have to assume, also, that the feeders have a given length. The reason for this is that with a system feeding a large number of substations, such as the system under discussion, the substations may be any distance from the power house, and before determining what the short-circuit current is, it would be necessary to figure the short-circuit current for each individual feeder. Therefore, to shorten the work, we must assume that the feeders have some average length. Furthermore, we do not know at what rate the current from the back feed of the substations dies down. You will see, therefore, we are trying to solve a problem where almost nothing is known accurately, and, consequently, the methods used in the solution must be applied with a degree of accuracy in mind which the problem warrants.

This leads to a point which may be of interest, namely, how may we approximate the probable value of the short-circuit kv-a. of a system? Fig. 14A, which has been referred to, gives a clue to one method of starting. A system with several generator bus sections and with a relatively large number of substations is usually not connected in the symmetrical manner that this figure indicates. If it is a new system, this can be done, but in the case of a system that is already in operation, or one that is growing, there is seldom one feeder from each bus section to each substation. To approximate the feeder layout we may take the number of feeders per bus section and find the average number of feeders on each bus section. Similarly we may take the number of feeders to each substation and find the average number of feeders per substation, and then we can construct a feeder layout which will resemble Fig. 14A.

Having constructed such a symmetrical diagram we may, for the purpose of simplifying the calculations, combine the various parallel paths to an assumed short-circuit location and resolve it into a one-line diagram.

Such a scheme is very useful in figuring the minimum reactances which will give a marked decrease in short-circuit kv-a. Some of Mr. Gross's curves show the amounts of reactance.

After going through all possible combinations of generator, feeder, group feeder, synchronizing, and bus reactors, we will find which one, for the particular system under discussion, best fits the conditions. Then, having decided upon that arrangement of reactors, more time can be spent in attempting to calculate accurately what the short-circuit currents will be.

Practically the same temperature rises given by Mr. Gross can be obtained by using transient direct currents of the same r.m.s. values as the alternating current, and decaying according to the same exponentials. The accuracy obtained is warranted by the assumptions which have been made in determining the short-circuit currents.

Mr. Gross gives two formulas for estimating the temperature rise of cables. The first one is for a symmetrical current wave and is not particularly involved, but the second one for an asymmetrical wave is rather cumbersome. Using formulas involving direct currents would greatly simplify the calculations.

H. R. Woodrow: I think if Mr. Davis will calculate again the short-circuit currents with feeder reactance coils he will find out a big advantage in favor of the feeder reactance coils where the feeders are paralleled in the substation. This is shown more clearly by the two values which were given, as a comparison between the plan submitted by Mr. Stott and the plan submitted by Mr. Torchio, where 50,000 amperes were given in the case of the split reactance scheme of Mr. Stott against 13,000 amperes as given by Mr. Torchio, and in both cases the figures were calculated on the assumption of paralleled feeders in the substation. In this case the feeder reactors limit the current both going and coming. That is, the current is limited by the feeder reactor leaving the other bus sections and again on the reactors leading into the damaged sections. We must remember in these calculations that 1 per cent reactance for a 4000-kv-a. feeder has the same ohmic value as 7½ per cent reactance for a 30,000-kv-a. bus section.

As referred to by Mr. Gross in the paper, the guaranteed breaking capacity of the oil switch is that of the best type of oil switch, which is large and expensive. Therefore a further reduction of the maximum short-circuit current is many times warranted to permit the installation of a cheaper and smaller switch.

We must bear in mind that the maximum forces are twice the average force given in this paper. The rigidity of conductor and supports determines the relative stress produced by the maximum or average forces.

As shown in Fig. 6, the maximum current occurs when the short circuit begins at zero voltage. The average current, under these conditions, for the first half-cycle is 60 to 70 per cent above the symmetrical condition. This produces an average force on an asymmetrical single-phase short-circuit 150 to 200 per cent higher than the values given in the paper.

As it is impossible to have a maximum asymmetrical current in all three phases of a three-phase short circuit, the forces produced by a single-phase short circuit in a given circuit may be more severe than with the corresponding three-phase short circuit. Therefore a rearrangement of the buses in a straight line will not reduce the maximum stresses, although the direction of the force may be changed to reduce the stress on the insulators.

The author has not mentioned the forces resulting from a heavy current in right-angle bends on the conductor. These forces are very heavy and do considerable damage to disconnecting switches and the T to the bus. The average forces are given by the equation $p = \frac{2 \times 10^{-7} I^2}{y}$ lb. per ft., where y is the distance on the T from the bus in inches. As the distance y is small the forces become enormous.

The author has assumed a constant resistance for the conductor in determining the temperature rise, but as there is a 35 to 40 per cent increase in resistance with a 100 deg. cent. temperature rise, this would produce considerably higher temperature than shown.

He has also assumed that all of the heat is absorbed by the copper. If the paper and oil is to be damaged, a portion of it must be heated, and as its specific heat is several times that of copper, the effect in reducing temperature rise is very marked.

The effects of these two conditions will offset each other to a great extent, so that the resulting temperature may be of the order given in the paper.

The effect on the result of equation (**17**) is very marked with a small impedance in the feeder circuit. As an example, if $Z_F = 0$, I_F would be zero.

This will bring the curves in Fig. 28 closer together, showing little effect of paralleling in the substation.

The effect of the results of equation (**18**) depends on the relative values Z_G and Z_F and may be considerable.

If the short circuit occurs on an end or any T to the synchronizing bus, the total curve given in Fig. 22 will be through one circuit, and the stress would be very severe.

Mr. Gross referred to the bus reactance as objectionable, due to the unbalance of voltage where only one generator was running. This of course can be avoided by short-circuiting the coils corresponding to the generators out of service and in no case will the short-circuit current be as severe as when all generators are running with all the bus reactance coils connected in the bus.

James Lyman: The formulas derived in this paper will simplify the determination of the possible stresses which take place in cables and busbars under short-circuit conditions, also of the possible temperature rise of same. The paper shows that the repulsive stresses are inversely proportional to the distance apart of the conductors measured from center to center of conductor.

The paper also shows that heating varies inversely as the square of the sectional area of the conductors. The larger the cable, the less mechanical disruptive strains on the conductors, the less danger of excessive heating on the conductor. In such distribution systems as the author has in mind, there is every reason to use as heavy cables as can be safely and conveniently handled, say for 11,000 volts, around 300,000-cir. mil cables.

I have been much interested in the discussion of protective reactors. The variety of schemes which have been presented in various papers before the Institute in this country and before the British Institution of Electrical Engineers shows what a really difficult problem it is. The problem is to get the minimum kv-a. reactance to give the maximum protection to the generators, the buses and the feeders.

John B. Taylor: If I read this paper correctly, the author, after considering possible sources of trouble, concludes that the one most likely to be serious is the overheating of a length of cable. The generators appear able to stand short-circuit strains, the buses are well supported; the mechanical strains, tending to burst a cable, seem to be well within the tensile strength of the wrappings, etc., so that it comes down to the question of what temperature the cable may stand, and the time to reach this temperature with a given current. Close attention therefore should be directed to the calculation of this temperature.

A previous speaker called attention to the fact that he did not see in the formula any temperature-resistance coefficient, but he concluded that this omission was not serious on account of other balancing factors. While the author's facility in handling the mathematical equation is to be admired, here, as always, mathematical conclusions are no more reliable than the facts and assumptions written down. If it is possible to arrange affairs so that the temperature of cable conductor will not go above, perhaps, 100 deg. cent., this omission of the temperature-resistance coefficient may not be vital. If I am right in my impression that for 200 deg. cent. rise, the resistance becomes doubled, at 600 deg. cent. rise the resistance and heat generation would be about eight times that allowed for in a calculation assuming constant resistance. The curves in the paper extend to temperatures where resistance must be increased sufficiently to make in error the times required to reach the higher figures.

If the short circuit is so located that the resistance of the cable is a factor in limiting the current, the resulting heating may be less, but, following the argument of the author of the paper, we must be prepared to meet the worst case of short circuit a short distance beyond the busbar, where the cable resistance is of no moment in limiting the current, and then the cable heating will be much more than his curves show.

The suggestion that the higher specific heat of the insulation wrappings is going to relieve the situation is to be questioned. While the specific heat may be higher than copper, the specific gravity is much lower, so that the insulation must heat to some depth before absorbing any considerable quantity of heat. Also, insulators for electric current are usually good heat insulators, *i.e.*, poor heat conductors.

R. W. Atkinson: It has already been mentioned that the data given are for the average force between the conductors and the cables or in the busbars. Now the forces are enormous as compared with the masses, and it seems from some very rough calculations which I have made that perhaps the maximum force is what would count, at least in the case of cables. This would be somewhat more than double the average force in the symmetrical wave, and I believe it would be somewhat more than four times as much as in the assymmetrical wave.

Now, we have been shown something of the magnitude of the forces, and it is of interest to note what are the magnitudes of the quantities which are resisting these forces. Mr. Stott mentioned them as being very large. We have in a foot of cable of the size mentioned about four or five square inches of paper, to withstand the force developed in the foot of the conductor. The tensile strength of that paper before it is applied is of the order of 8000 lb. to the sq. in., so that we would have something like 30,000 or 40,000 lb. as the ultimate strength of the paper if it retained its original strength. Of course it has lost much of that strength by the time it is put on the cable and pulled into a duct, but even then, there remains, when the cable is new, a very large factor of safety for the order of magnitude of current which is recommended as the maximum safe current. After the cable has been overheated for a few months or years, the strength will be not nearly so large, and these forces will be of more importance. Thus, one of the possibilities is that these forces which exist will tend to reduce the life of a cable which has not deteriorated as far as its electrical properties are concerned, but which has deteriorated with respect to its ability to withstand these forces.

The matter of the temperature coefficient of the resistance of the conductor has been brought up, and it is evident, from what has been said, that to take that into account in a mathematical formula would be a pretty complicated matter. Suppose the resistance does double, evidently we should not use the initial resistance in the calculation. It would not be a very complicated matter to exercise a little judgment, and use, in the formula, a resistance which would approximate the effective resistance, and I suppose that is about what was done in making the tables.

The effect of high temperatures upon insulating materials has been previously discussed before this Institute. The direct reduction of dielectric strength is not so important as the change of other properties. Even at the operating temperatures there is a very slow deterioration of mechanical properties. But the fibrous insulating materials used in cables may withstand without material permanent change, for a very brief time—perhaps only a very few seconds, temperatures of even 200 or 300 deg. cent. Of course, if such temperatures are reached in a large cable, dangerous temperatures will be maintained for some time. Also, if working voltage is reapplied while the cable is at an abnormal temperature, the cable is in danger of further overheating and ultimate destruction due to the dielectric energy loss which becomes very great at high temperatures.

If the copper gets red hot it chars at least some of the layers next to it. Just as a rough method of seeing what might happen, I put enough current through a No. 8 conductor to melt it in about four seconds. The No. 8 conductor was insulated in the same way that the high-tension cables mentioned in the paper are insulated. The effect of this heating was to char completely one or two layers next to the conductor; the rest of it was unaffected. A very noticeable effect was the extremely large amount of gas given off due to the destruction of only one or two layers of papers. It is possible that a short circuit which would heat the copper enough to char very much of the paper might destroy the lead cover by the gaseous pressure generated.

All of these things are subject to experiment, and the actual limit of overheating which a conductor will stand, due to the effect on the insulating materials of these very high temperatures for a brief time, is an important problem, and the determination of these things seems to be of a good deal more importance than the knowledge of whether the temperature rise is 10 per cent or 25 per cent more or less than some particular formula will show. These things and the effect of the enormous mechanical forces which are developed can be determined by not expensive experiment.

Charles L. G. Fortescue: The degree of protection made against any contingency should be based on its probable frequency and the extent of damage that would result therefrom. With a normally designed system, short circuits are much more frequent in the feeders than in the station buses, and therefore proper protection requires that a short circuit in any feeder be relieved with the least possible disturbance to the system. It appears to me that a protective layout which permits a short circuit in a single feeder to cause as much disturbance as a short circuit at the buses is inadequate. It seems to me that scheme *S*-1, Fig. 14, and the similar schemes shown, would afford better protection if reactors equivalent in effect to Z_B were placed in each of the feeders, each feeder of course being provided with an automatic breaker, while Z_K is decreased and Z_G correspondingly increased. In other words, a combination of Mr. Stott's scheme and the feeder reactance scheme appears to have distinct advantages over either.

Hans Lippelt: In the recent past we have repeatedly heard of reactance coils as protective devices, but little attention has been paid to the question of efficiency, which, however, should be considered whenever an apparatus is being employed. As our president has remarked tonight, reactance in an a-c. circuit was formerly dreaded like poison, and mainly so on account of the increased losses caused thereby. The fact that artificial reactors are nowadays provided for the protection of large generators does not mean that the poison has been taken out of them. On the contrary, the losses incurred by installing reactance coils have rather increased, because the strength of current passing through them has reached, with large units, enormous values. As we all know, the losses through reactance coils are principally two-fold. First, the power factor is being reduced, which diminishes the output capacity of the generators. Second, for a given power to be transmitted, the strength of current must be increased just on account of the smaller power factor. Higher values of current entail larger I^2r losses, and this feature is the greater evil of the two, because it has to be paid for.

As we have learned today, a small reactance coil (say 5 per cent) affords only limited protection. For instance, it may permit 100,000 amperes, or more, to pass through an oil switch (Figs. 20, 21, etc., of the paper), indeed an undesirable condition, which is still more aggravated when the oil switch opens the circuit. While the reduction of power factor and the increase in I^2r losses may be bearable, the danger which still slumbers in the system is great. The destruction of an oil switch when opening under short-circuit conditions, may, in effect, not fall short of a boiler explosion.

By increasing the amount of artificial reactance the vehemence of short circuit may be held within limits as prescribed by the electrical and mechanical ability of the system. In order to obtain such a condition, reactance must be so high that operation of plant becomes uneconomical.

Would it not be better to attack the evil at its root by changing the electrical system as a whole, instead of only attempting to improve a part of it?

What I wish to propose is a direct-current system at high operating voltage. It may be 11,000 volts for the case discussed in Mr. Gross's paper. How to generate and operate direct current of such voltage, is too early for me to say, but I wish to point out briefly the advantages of a high-voltage d-c. system.

Protection is required for direct current the same as for alternating current, but it may be obtained with more reliability and without impairing operation or efficiency.

Reactance coils of high self-induction may be employed and yet the power factor will always remain unity. There will be no increase of current necessary to transmit a given power and the I^2r losses will not be more than before the introduction of coil. I^2r loss of coil is negligible. After all, the reactance coils should be provided with iron cores. In order to make the coil fully effective a resistance should be employed in connection with it. Referring to the accompanying Fig. 1, Z_G represents the generator reactance coil with iron core, and R_G a resistance which is ordinarily short-circuited by switch S_G. Part of iron core is made movable and serves to operate switch S_G.

In case of a short circuit our apparatus will, owing to its high inductance, delay the occurrence of the maximum value of current (one second, or more, seems possible). During this delay switch S_G will be opened and resistance R_G introduced, with the effect that the maximum amount of current will be kept down to reasonable magnitude. For a 30,000-kw., 11,000-volt generator, 3½ ohms only will suffice to hold the current down to about 20 per cent overload, which does not mean any danger at all to the generator. Besides, there is no possibility here of synchronous apparatus falling out of step.

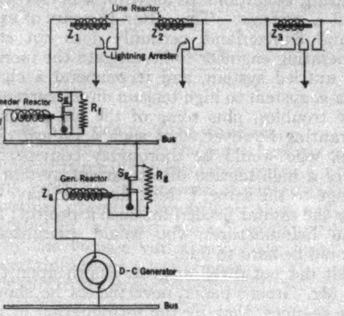

FIG. 1

Other reactors may be installed in the system for the protection of parts of same. The accompanying Fig. 1 shows iron core reactors installed at intervals in an overhead line, in connection with lightning arresters. By proper design of reactor, lightning strokes will be localized to a section, and diverted to ground. The iron cores will come into action when the surge begins to set in, and will throttle it down.

Such results cannot be obtained with a-c. systems. High-voltage d-c. systems are now being favored by engineers abroad, The transmission of 12,000 kw. from Sweden to Denmark by 90,000-volt direct current in a cable at the bottom of the sea, is a striking example of it. (See *Electrical World*, February 8, 1913, page 294.)

S. I. Oesterreicher (by letter): From the unchallenged remarks of Mr. Lippelt, at the last Institute meeting, about the advantages of a high-tension direct-current system over a similar alternating-current system, it might appear that the Thury d-c. system is immune from disturbances and reactor losses as experienced on large a-c. systems.

Among the several contrary opinions to the above statement, I beg to go on record as one who claims that Mr. Lippelt's statement will not be able to stand up if investigated.

There are no available data upon which to base a somewhat reliable comparison between a-c. systems of the magnitude and severe operating conditions as described in Mr. Gross's paper and similar d-c. systems. This, after 15 years of experimenting in France and Switzerland, certainly does not encourage an American operating engineer to investigate the merits of an uncertain and untried system, and recommend a change from a well-known a-c. system to high-tension direct current, with some entirely new troubles, plus some of the old tricks of the a-c. system. Granting however, that such a radical operating engineer exists, who would be thoroughly convinced about the advantages of a high-tension direct-current system and recommend a change to the same, I think he would have a little difficulty to raise the capital needed for such a project; furthermore, an American manufacturer who would guarantee a reliable operation would be hard to find.

Mr. Lippelt did not dwell at great length upon the merits or demerits of Mr. Gross's paper, nevertheless he showed us in a very capable manner, that by the introduction of reactance in alternating-current circuits, the current wave will lag behind the e.m.f. wave, which means loss of energy; and while perhaps some electrical engineers suspected such conditions, he certainly took everybody by surprise, when he stated that iron-core reactors in high-tension direct-current systems are immune from losses and disturbances.

I beg to ask Mr. Lippelt to give the Institute data from actual high-tension direct-current practise, where iron-core reactances are used and where on such systems such coils are immune from hysteresis losses. Until such a time I beg to claim that iron core reactors on the Thury system will behave—with certain numerical modifications—in the same way as on alternating-current circuits. This on account of the Thury system, which, speaking theoretically, is not a direct-current system in the sense of the storage battery, but an alternating-current system, changed by commutation into a wave of very flat shape, of either positive or negative sign, or perhaps both, and having a frequency equal to the rev. per sec. times number of commutator segments, divided by the number of the brush groups. The height of the wave will be determined partly by the generator characteristics and partly by the regulation of the line. Any oscillograph will easily prove this fact.

Now let us assume the high-tension direct-current project from Trollhaetten to Copenhagen, the one mentioned by Mr. Lippelt, and let us assume that this line will have a regulation of one-half of one per cent at normal operating conditions, or, as per the potential given us by Mr. Lippelt, for 90,000 volts, this line voltage would fluctuate 450 volts.

Since there are no available data about the characteristics of the Thury generators, we will omit them from our consideration, with the additional remark that these generators are insignificant in size, when compared with the units mentioned in Mr. Gross's paper.

A fluctuation of 450 volts in the line will set up a flux in an iron core of

$$\frac{450 \times 10^8}{4\,F_e\,f\,N\,.\,.\,.\,.\,\text{lines}}$$

where F_e is the form factor of the wave shape,
f, the frequency, or in this case the pulsations per second, and
N, the number of turns in the reactance coil.

From this equation it becomes apparent that, even under the most normal operating conditions, there will be a counter e.m.f. generated in the reactance coil winding, due to the flux generated by the voltage variations of the line. This counter e.m.f. will certainly mean a loss of energy. The energy required to set up the flux in the iron core will also be a loss.

When considering a large system, consisting of six 30,000-kw. generators, feeding into a fluctuating railroad load, with say 15 times normal load as the maximum short-circuiting current, it will be a simple matter to realize that iron-core reactance coils will be very little better—if not worse—on high-tension d-c. lines, than our air-core reactances in their a-c. circuits.

Summing up, I believe that the Thury high-tension direct-current system will not as yet solve our present metropolitan energy distribution problems. It will not solve them, first, on account of its unreliability of operation as experienced in southern France; second, it will offer no better protection against operating disturbances, and last but not least, on account of its rather complicated station wiring, when compared with our high-tension a-c. generating stations.

Alfred E. Waller (by letter): Mr. Gross's statement "In a paper-insulated lead-covered cable, the force is exerted on the over-all wrapping around all three conductors" appears to me incorrect. It would be true if the conductors were straight bars arranged parallel to each other in the triangular spacing indicated, and under the assumption of current conditions given by Mr. Gross in his discussion. The conductors of a high-tension cable of this kind are laid like the strands of a rope and form spirals parallel to and at equal distances from each other. Hence any motion radially away from the center of the cable implies increase in the diameter of the spiral, and this could be attained only by elongation of the conductors. The conclusion is that the stresses set up by the condition which Mr. Gross proposes, would be taken up by the copper itself and not by the wrapping. As a matter of fact an equal r.m.s. current of the same sign in each conductor of the three-phase cable, would probably never occur. A normal if not inevitable condition would be presented if one conductor were assumed to carry current of different sign from the other two, and equal in volume to the sum of the current in the other two conductors.

Philip Torchio (by letter): In Fig. 14D of my remarks, I have shown busbar reactors and feeder reactors in contrast with Mr. Stott's arrangement, shown in Fig. 14. A recent patent, issued to Messrs. Torchio and Woodrow, gives a combination of mutually inductive reactors, as shown in Fig. 14E, where generator and busbar reactors are combined in one coil mutually inductive. By so doing, they secure not only generator protection but increased efficiency of the busbar reactors, in reducing potential drop, for the reason that the short-circuit current, in one section of the system, is made to assist in keeping up the voltage on the other sections not directly involved in the short circuit.

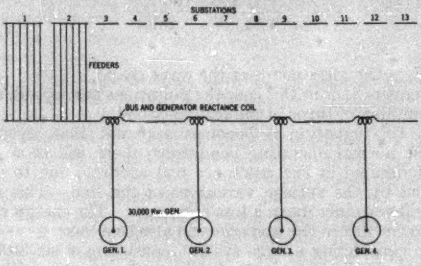

FIG. 14E

This combination would give similar advantages in Mr. Stott's arrangement if the synchronizing reactor and the feeder group reactor were combined in one mutually inductive reactor, thereby securing the following advantages:

1st. The space required is very much less.

2nd. The mutual inductance between the two sections of the coil limits the current to a greater extent for a given amount of copper.

3rd. A short-circuit disturbance causes less voltage drop on the remainder of the buses, as the current in the short circuit is made to assist in keeping up the pressure on the rest of the system.

I. W. Gross: Several of the points which have arisen in the discussions have been answered wholly or in part by those which follow.

Mr. Torchio's comparison of Mr. Stott's plan of feeder bus and synchronizing reactance with his own plan of feeder and busbar reactance, is very misleading, to say the least. Take the condition of " Short circuit on a feeder—Feeders in parallel at substation." In Mr. Stott's plan there are two methods of paralleling feeders at the substation: one as shown in Fig. 14, where any substation receives power from only one bus section, the feeders being paralleled on a common bus at the substation; and the other as shown in Fig. 14A, where all substations have at least one feeder from each bus section.

In the former Fig. 14, you lose flexibility at the expense of a decreased short-circuit current; in the latter, Fig. 14A, the opposite is true. With the former scheme the feeder short-circuit current is only 23,600 amperes regardless of whether the feeders are paralleled at the substation or not, and this is less than twice the current in Mr. Torchio's plan.

Further, when the short circuit occurs on the bus only one-fifth of the current of 88,000 amperes, or 17,600 amperes, is required to be opened by any oil switch. No danger from overheating exists, as the heavy busbars are perfectly capable of carrying this current for a short time.

In Mr. Torchio's scheme the entire current of 76,000 or 81,000 amperes may have to be broken on a small feeder oil switch. This is obvious if the short circuit occurs between the pots of the oil switch and the feeder reactance. Under this condition of short circuit Mr. Woodrow's " cheaper and smaller oil switch " which would safely break 12,000 to 13,000 amperes, would unquestionably fail when required to break 76,000 amperes.

In brief, then, it appears that Mr. Torchio's plan, instead of furnishing more than treble protection over Mr. Stott's scheme, in reality provides less than one-third the protection, that is, 76,000 against 23,600 amperes, and will likewise require a larger and more expensive feeder oil switch for full protection.

Mr. Torchio, after comparing the two schemes on an equal cost of reactance basis, adds that, " in practise it will be found necessary to install the 1 per cent feeder reactance and 2 per cent busbar reactances," thus admitting the greater cost of his scheme.

I do not wish to minimize the value of Mr. Torchio's scheme; for the protective worth of the feeder reactance scheme and the busbar reactance plan are well known, and a combination of the two will undoubtedly do what neither can accomplish alone.

I thoroughly appreciate Mr. Davis's discussion of the inaccuracies and approximations which enter into an analysis of this kind. The computations involved when taking actual feeder lengths, which in our case varied from less than one mile up to over eight miles, and number of cables, which were as few as three and as many as seven, become most complex.

In the curve for Fig. 27, as noted by Mr. Woodrow, the effect of the relative value of impedance in the circuits may be considerable.

The effect of paralleling of feeders at the substation end is therefore considerable, and increases still more as the number of feeders to a substation increases. This applies only where feeder reactance is used, or in Fig. 14A, where the feeders to any substation are distributed among several or all of the feeder bus sections.

The effect of temperature coefficient on the computed temperature rises can best be taken care of by "the exercise of a little judgment," as suggested by Mr. Atkinson. Having decided upon the maximum temperature you wish to allow in the copper, merely use the resistance of copper for that temperature, and assume this resistance as existing throughout the entire period of heating. This, of course, would allow a margin of safety, as at the instant of short circuit the resistance would be considerably below the value actually used. Another method would be to take the resistance at a temperature one-half of the maximum you wished to allow. This would undoubtedly give a very close approximation to actual ultimate temperature.

A value of 11 ohms per cir. mil-ft. was used in the paper.

In Fig. 14A, or a modification of the same by allowing feeders to any substation to come from only two feeder bus sections, that is, sectionalizing the substations by groups, Mr. Torchio's patent reactance scheme of combining the feeder bus and synchronizing reactance into one coil, would have the effect of tending to increase the current through the oil switch of the feeder undergoing short circuit. For, while choking off any current which would tend to flow from the other four units, it would thereby maintain a higher bus voltage which would be impressed on the feeders interconnecting with other substations, and thence feeding back through the feeders to the affected bus section. Thus the net effect might be to increase the short-circuit current through the oil switch.

Presented at a joint meeting of the Philadelphia Section of the American Institute of Electrical Engineers and the Franklin Institute, Philadelphia, Pa., January 20, 1915.

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CONDITIONS AFFECTING THE SUCCESS OF MAIN LINE ELECTRIFICATION

BY W. S. MURRAY

ABSTRACT OF PAPER

In this paper are laid down the conditions affecting the success, for both the public and the railroad, of a main line electrification project, as they have developed in the author's experience with the New Haven 11,000-volt, 25-cycle, single-phase, overhead contact system. Reliability of service and comfort and cleanliness in operation constitute success from the point of view of the public, while the railroad requires, in addition, economic success. Success is dependent, apart from the engineering, construction, and operating features, entirely upon the *density of traffic.*

A commercially successful electrification is one which cuts the operating expenses of steam-operated territory it has replaced to a figure such that the savings effected are sufficient to justify the investment. The savings in operating expenses made by electrification are, in the order of their importance: saving in fuel; saving in motive-power maintenance and repairs; saving in train-miles.

As specimens of the reliable data being obtained from the operation of the New Haven system, statistics from a recent monthly operating report are presented in tables as follows:

1. The amount, distribution and cost of electric power generated at Cos Cob station.
2. Statistics and operating costs of electric passenger service.
3. Statistics and operating costs of electric freight service.
4. Statistics covering line and equipment failures.

Tables are also presented showing construction costs for catenary construction of different types, including anchor and sectionalizing bridges.

BEFORE touching upon the conditions affecting the success of main line electrification, perhaps it would be best to address ourselves to the question as to what constitutes success. A successful electrification may be considered as such from several viewpoints, and this leads to the necessity of a clear understanding with regard to projected results, both on the part of the railroad and the public.

A successful electrification means, of course, successful transportation by electric motive power. Classifying success into its broadest terms, an electrification may be:

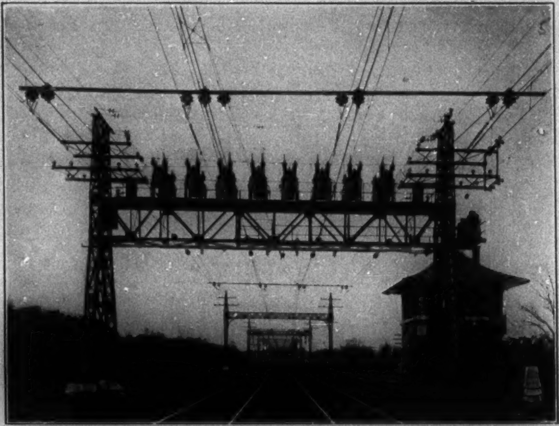
1. A success for the public.
2. A success for the railroad.
3. A success for both the public and the railroad.

Naturally the greatest objective is the attainment of No. 3 of the above classification.

The railroad is vitally interested in the pronouncement by the people as to whether its electrification is successful or not, and, while the viewpoint of the railroad is identical with that of the people throughout their range of vision, looking at it, however, from the purely railroad side, a successful electrification, besides this, must answer the dictates of good business, which in turn are governed by the rules of economic consideration.

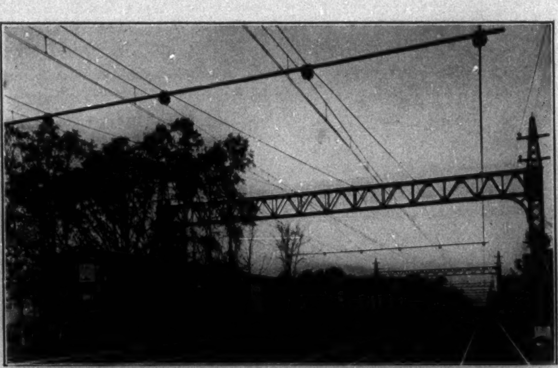
In latter times the tremendously decreased gross earnings and a complementary increase in operating expenses have so greatly reduced the net incomes of the railroads that the public have awakened to the fact that they are staggering under a financial load which, if not modified or alleviated in some way, will shortly make receivership the rule rather than the exception.

A few years ago a movement was started by the public to require the railroads to electrify, this being directed towards roads of large size with their attendant city yards and terminals. There were two principal and logical factors against the justice of this demand, the first being that at that time there was very little statistical information as to form, application, and economic result of electrification; and, second, due to the extremely grave financial situation as above described, it was patent that the railroads could not possibly carry the increased financial obligations that such a demand necessitated. The public were thus brought face to face with the undeniable conclusion that they were demanding something impossible, and so there has been a pause on their part, which has indeed been gratefully received by the railroads of this country. Let it be said that this very pause will later shed its dividends over many, for during this time the few railroads that had committed themselves to electrification have had an opportunity to study it in all of its important details and ramifications, and later, after an adjustment has been made whereby the solvency of the railroads of this country is guaranteed by a proper relation between transportation rates and operating expenses necessary to the safe conduct of their business, with enough left over to provide a reasonable return on a fair valuation of the property in use, then, and only then, will the railroad companies be able to do what today they cannot, namely, attract new capital required for electrification; and so, while a reference to this matter may be slightly off the subject of this paper, yet I cannot but take this



[MURRAY]

FIG. 1—FOUR-TRACK TANGENT COMPOUND CATENARY CONSTRUCTION
Showing anchor bridge in the immediate foreground, with sectionalizing switches installed thereon. Signal tower is seen at the right of the tracks, and from this tower sectionalizing switches are controlled. Note also crossover under anchor bridge, with its overhead contact wire.



[MURRAY]

FIG. 2—SIX-TRACK TANGENT COMPOUND CATENARY CONSTRUCTION
Showing electric freight locomotive and train. Freight trains are operated between Harlem River and New Haven, the normal maximum tonnage of which may be, with double locomotive and multiple-unit control, up to 3150 tons. The introduction of freight hauled by electricity has permitted the division to increase the steam tonnage rating twice, reduce time by 33 per cent and train crew expenses to one-half.

opportunity to say in the abstract that this is indeed an important condition precedent to successful electrification.

The pause has given us a chance to learn many things about electrification. I do not believe that I would be conveying information to many who have studied the subject to say that there are probably one hundred places at this moment where conditions are such as to ensure successful electrification. For example, there is one situation I have in mind where an expenditure of $5,000,000 would yield beyond peradventure a return of 20 per cent—this as measured against the present steam operation of the territory contemplated for electrification; and yet in the same breath it might be said that if the yield could be shown to be 40 per cent instead of 20 per cent the electrification of that territory would be denied, and rightly, too. Why? Because, for roads sufficiently large to consider electrification, a sum of this size is small in comparison to their existing capital investment, and a proper relation must first be established between capital already invested and the return upon it before further charges against capital account are made, no matter how attractive the return on the proposed betterment may be.

Quite a number of trunk line railroads, both in this country and abroad, have been studying electrification. The New York, New Haven and Hartford Railroad has not only been studying it most carefully, but has also had the opportunity of assembling data from the practical experience of operation with a range of application that includes all classes of transportation. Millions of ton-miles in these several services have been actually recorded in the logs of the road's operation. In passenger service alone for the year 1913, 2,182,000 electric passenger locomotive-miles were recorded, which alone would represent approximately 600,000,000 ton-miles. The part of the New Haven system that has been electrified constitutes its most important division, extending from New Haven to New York, and on its main line, yards, sidings, and spurs every class of railroad movement is being daily made by electricity. A brief physical description of this division may be as follows:

Route mileage electrified, 73 miles, of which 61 is of four tracks and 12 of six tracks, thus giving a total main line mileage, measured in single track, of 316. To this may be added 184 miles of yards, sidings, and spurs, thus making a grand total, measured upon a single-track basis, of 500 miles. It is of interest to note that of the yards electrified one includes 35 miles, the other 25 miles.

Electric power is supplied to this extensive mileage from a single station, centrally located, but which, in a short time, will be supplemented by other supplies to be applied at the east and west ends of the electrification zone. There are 100 passenger, freight, and switching electric locomotives, and 69 multiple-unit cars. One main electrical shop has been completed, the capacity of which permits the maintenance and repairs of the above-mentioned electric motive power. Facilities for inspection of electrical equipment are also provided at various points in the electrification zone, the more important points being, of course, at termini.

To date, over $15,000,000 has been expended on this electrical transportation plant as above described. While such a figure represents the cash outlay, they have accrued to its appropriation accounts, during the process of construction, large credits for steam equipment replaced, as, for example, the 150 steam locomotives which have been transferred to other parts of the New Haven system, and the steel bodies of the multiple-unit equipment, which would have been purchased even had not the electrification been undertaken.

Descriptive of the electric movement on the New Haven electrification zone, the following facts with regard to passenger, freight, and switching service may be of interest:

Passenger. At the present time all passenger service west of Stamford, Conn., is electrically operated. For the winter time-table now in effect, excluding Sundays, the schedule calls for 68 trains per day into Grand Central Terminal, two through trains terminating in Harlem River Station and the same number of trains out of the Grand Central Terminal and Harlem River, or a total of 140 trains per day.

The Harlem River Branch service includes 19 trains each way per day, except Sundays, between New Rochelle and Harlem River.

On the New Canaan Branch 16 trains are operated each way between Stamford and New Canaan.

This makes a total week-day schedule of 210 trains per day. Additional trains in and out of Grand Central Terminal are operated on Saturdays, and extra trains are also run on the Harlem River Branch on Sundays.

Of the 70 through trains per day between Grand Central Terminal, or Harlem River, and New Haven, 46 are electrically operated the entire distance, steam locomotives being used between New Haven and Stamford on the remaining 24 trains.

Of the 210 trains per day, 114 are hauled by electric locomotives, multiple-unit equipment being used on the remaining 96 trains.

Forty-eight a-c-d-c. locomotives are used in passenger service. The multiple-unit equipment at the present time comprises four a-c. motor cars, 21 a-c-d-c. motor cars, and 46 trailers.

The average number of electric train-miles per day is about 6600, of which 1400 are made by multiple-unit equipment, the remaining being trains hauled by electric locomotives.

The passenger locomotives make an average of 8200 miles per day, some of the individual locomotive mileages being as high as 450 to 500 miles. Forty-one of the 48 passenger locomotives used in a-c-d-c. service were originally designed to haul trains of 200 tons trailing weight in local service, 250 tons in local express service, and 300 tons for through express service between New York and New Haven. At the present time two of these locomotives are only used on through express trains where the trailing weight exceeds 390 tons, and two locomotives may also be used on heavy local trains.

New flash boilers have recently been installed in these 41 locomotives, of increased capacity, to provide for steam heating of through passenger trains between New York and New Haven. This is accomplished successfully. Through service between New New York and New Haven was inaugurated in June, 1914, and these locomotives easily make their running time in express service.

The remaining seven a-c-d-c. passenger locomotives were originally designed to haul local trains of 350 tons trailing weight or express trains of 800 tons trailing weight at a maximum speed of 45 miles per hour. In actual service these locomotives attain a maximum speed of 55 miles per hour.

The multiple-unit motor cars make an average of 2100 miles per day. The proportion of trailers to motor cars for a-c-d-c. equipment averages two trailer cars to one motor car. On the New Canaan Branch the proportion is one trailer car per motor car, while on the Harlem River Branch about one-half the trains have two trailers per motor car, the remaining trains consisting of a motor car and one trailer.

Of 96 trains operated per day by multiple-unit equipment, 38 are Harlem River Branch locals, 32 are New Canaan Branch locals, and the remaining 26 are either locals or local express trains between New York, New Rochelle, Port Chester, Stamford, and New Haven.

Freight. Thirty-six a-c. locomotives are used in freight service. These are geared locomotives of 1400 h.p. each and designed originally to haul a trailing load of 1500 tons in through service at 35 miles per hour, although they are used at times for heavy passenger service in the a-c. zone during the summer months, when heating of the trains is not required. Some of these a-c. locomotives are used in transfer service between Oak Point and Westchester freight yards on the Harlem River Branch, others in way freight and switching service, but the majority are used on through freight trains between Harlem River and Bridgeport or New Haven. Outside of the fast freights, which are usually under 1500 tons trailing weight, most of the freights are hauled by two locomotives, the trailing tonnage averaging from 2500 to 3000 tons, although, as an experiment, tests have been made in using three locomotives with trains of over 200 cars and 4500 tons trailing weight.

About 20 freight trains are hauled daily at the present time by electric locomotives between Harlem River and Bridgeport or New Haven.

Switching. Electric switchers are used in the three main switching yards on the Harlem River Branch, located at Westchester, Oak Point, and Harlem River; likewise at Stamford, Port Chester, New Rochelle, Mt. Vernon and at Van Nest, the latter yard being principally used for storage.

At Oak Point and Harlem River the switchers are used principally for unloading and loading floats and making up trains. One switcher was placed in service in March, 1911, at Stamford, and the remaining 15 have been in operation since September 1912. They have been highly successful in operation, and their reliability is evidenced by the fact that to date there has only been one case of grounded main motor, although the 16 locomotives have made approximately 50,000 miles each. Some of these locomotives have been at times in continuous service 24 hours per day for 30 days, the only attention received being the renewal of blower or compressor motor brushes, or contact shoe of pantograph trolley at such times as change was made of the operating crew.

Four of these electric switchers have been found to do about the same work as six of the steam switchers, which they have displaced, principally on account of the fact that the electric switchers can be used almost continually with no lay-over periods. On account of the simplicity of the equipment on these locomotives, used only on alternating current, compared with the more complicated equipment used on the a-c-d-c. locomotives, no trouble has been experienced in breaking in new men, and, as a rule, the engineers need comparatively little preliminary instruction when being transferred from a steam locomotive to an electric switcher.

Mercury Rectifier Car. For some time a motor car has been in service which has been equipped with a Westinghouse-Cooper Hewitt mercury arc rectifier and four 250-h.p. motors. After a period of experimental runs on the Harlem River Branch, this car was placed in commercial service on the New Canaan Branch on September 16, 1914, hauling two trailers, the weight of the trailing load being 76 tons. In this service the motor car has been making an average of 240 miles per day. During the time the car has been in commercial service two delays due to failure of the equipment on the motor car have been recorded—one of three minutes on October 13 due to poor contact of a control interlock finger, and one of sixteen minutes on October 16, due to a broken belt on the circulating water pump.

In 1905, when it became necessary for the New Haven Road not only to actively consider electrification, but promptly decide upon the system to be used, as there was but a scant two years left between that time and the date set by the decree of the New York Court for all New Haven and New York Central trains to operate by power other than steam through the Park Avenue Tunnel, a careful study into the conditions surrounding the New Haven requirements pointed to the necessity of a system different in principle and arrangement from that which had been decided upon and very nearly completed by the New York Central Company—not that the New York Central Company had not made a choice of system which was entirely correct, but because the New Haven conditions were so entirely different from those of the Central. If we regard the New Haven electrification a success, here we must first note conditions that had to be reckoned with to ensure that success.

It was plain to the engineers who had studied these conditions that even in that early day, when the direct-current, 600-volt, third-rail system was at the height of its efficiency and popularity, it would fail by far, when examined upon an economic basis, in the result that would be secured in the use of the high-voltage, single-phase system.

In those days our experience with the a-c. system was *nil*;

a clear vision as to the correctness of its principles, however, more than replaced this lack of experience. To many these were strange arguments to use against a well-tried-out and accepted system, and, while deeply sensible of a period both difficult and trying to the operators of the road, the burden of this decision had been made light by a willingness on the part of all to take a perspective rather than a foreshortened view of the situation as it has gradually worked its way out of its initiative troubles.

A storm of criticism from all parts of the world assailed our conclusion. As this, however, is ancient history, to say more along these lines would be to say less. This paper, however, might lack a detail not to mention the real reason for which a paper, entitled *The Log of the New Haven Electrification*,* presented in 1908 before the American Institute of Electrical Engineers, was written. It seemed to the writer that the thick layer of criticisms shortly after electrical operation was inaugurated, on top of the number that had been received before, required that the discussion be held down to the actual facts in the case, and, knowing that the principles upon which the New Haven electrification was based could not be assailed, and that the log sheet of operation, bad as it was, was merely a reflection of the minor details common to initiative in all new undertakings, it were best to write a paper of the faults that had appeared and the methods used for their correction. This had the desired effect, as the discussion since then has been held within the facts.

It took not a great while to determine upon and eliminate the causes incident to the failures which reflected deleteriously upon the service of the road, and, while the reliability of operation in the electrical zone rose to some three or four times that of the steam operation it replaced, it was not then or even now what it will ultimately be. At this point we touch upon one of the conditions to be satisfied in order that an electrification may be called a success; namely, reliability of service.

The replacement of a steam service which had never been criticised, by an electrical one of increased reliability, naturally brought the pronouncement of success by the public. Indeed, since those first days after the elimination of the troubles which assailed us in our initiative operation there has never been anything other than a favorable comment, both on the part of the public and the technical press. Naturally this was most encouraging to the New Haven engineers.

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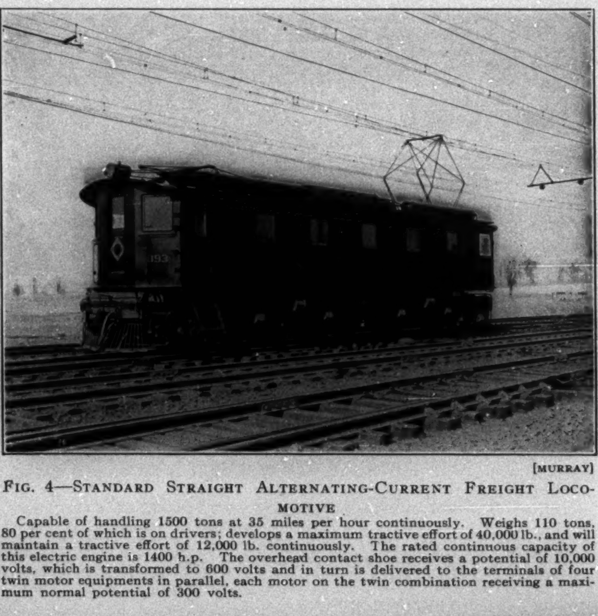
* Trans. A. I. E. E., 1908, XXVII, Part II, p. 1613.

[MURRAY]

FIG. 3—VIEW IN WESTCHESTER YARD, HARLEM RIVER BRANCH

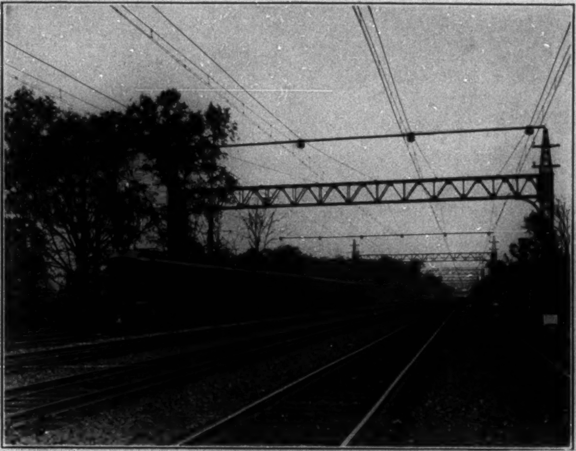
Showing overhead construction used in electrifying large yards. The cross catenary span in the immediate foreground serves ten tracks. In the case of the Harlem River Yard there are single spans serving eighteen tracks. For equal electrical energy delivered, the cost of this construction is one-third that of the third-rail.



[MURRAY]

FIG. 4—STANDARD STRAIGHT ALTERNATING-CURRENT FREIGHT LOCOMOTIVE

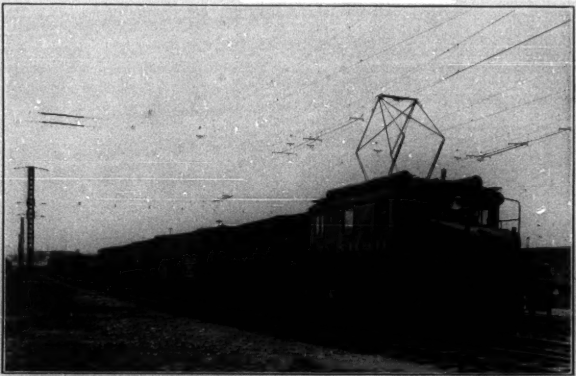
Capable of handling 1500 tons at 35 miles per hour continuously. Weighs 110 tons, 80 per cent of which is on drivers; develops a maximum tractive effort of 40,000 lb., and will maintain a tractive effort of 12,000 lb. continuously. The rated continuous capacity of this electric engine is 1400 h.p. The overhead contact shoe receives a potential of 10,000 volts, which is transformed to 600 volts and in turn is delivered to the terminals of four twin motor equipments in parallel, each motor on the twin combination receiving a maximum normal potential of 300 volts.



[MURRAY]

FIG. 5—MULTIPLE-UNIT TRAIN OPERATING ON SIX-TRACK HARLEM RIVER BRANCH ELECTRIFICATION

This multiple-unit train is also designed for operation on the New York Central direct-current third-rail system. Each motor car has sufficient capacity to haul itself and two trailers.



[MURRAY]

FIG. 6—ELECTRIC SWITCHER NO. 0213, DOING REGULAR SWITCHING SERVICE IN OAK POINT YARD

Four of these engines are capable of doing the work of six steam switchers. They weigh 80 tons, with 100 per cent weight on drivers. They will develop 40,000 lb. tractive effort, and will maintain a tractive effort of 12,000 lb. continuously. Sixteen of these electric engines have recorded over 1,200,000 miles in switching service, and one failure, a burned-out armature, due to a prolonged and excessive load from brakes sticking, is the record of their performance to date.

About three years following the presentation of *The Log of the New Haven Electrification*, the writer ventured a second paper, entitled *Electrification Analyzed, and its Practical Application to Trunk Line Roads, Inclusive of Freight and Passenger Operation*,* this also being under the auspices of the American Institute of Electrical Engineers, the intention being to present such electrification construction and operating data as he had collected to date, the object of the paper being to show the adaptability of electricity to extensive trunk line movement in all of its branches, covering passenger, freight, and switching on terminal and main line tracks.

In presenting the paper the writer purposely avoided a reference to comparative costs of operation between steam and electricity for two reasons: The first, because of the fact that only a part of the whole division was electrified, and an extremely expensive interchange of steam and electric operation had to be maintained, necessitating expensive duplications and special arrangements which would not have been common to either system had one or the other been used in its entirety upon the whole division. The second has reference to the matter of construction costs, which were exceedingly high in the case of the original electrification between Woodlawn and Stamford—the first undertaken. I am sure it will be of interest to state that in the original electrification the unit cost in 1907 for the four-track overhead system was just double the amount expended on the four tracks recently completed in the section between Stamford and New Haven.

In the discussions before the American Institute of Electrical Engineers and the American Society of Civil Engineers repeated requests were made for a presentation of the construction and operating costs in connection with the New Haven electrification. For the reasons above cited, and because of the fact that the New Haven electrification was decidedly handicapped in being required to build its motive power equipment to operate with either alternating current or direct current, the writer concluded that the time had not arrived where a presentation of these details would serve a useful purpose. Especially was this true in the bitter war that was being waged by parties who were prone to look upon the single-phase system of traction as deterrent to the application of the "more reliable direct-current third-rail system"—then in the flower of its youth, but since gone to seed! (I, of course, have reference to trunk lines.)

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*Trans. A. I. E. E., 1911, XXX, Part II, p. 1391.

Here was the problem the engineers of the New Haven Road had placed before them: the consideration of an electrification, the demands upon which would be far beyond any other hitherto constructed or contemplated. The conditions and principles applying to the past and smaller electrifications did not apply to it. Which were to control—the correct principles with the failures always common to initiative, or the wrong principles with a sureness that the service for possibly a number of years would be of a more reliable character? Some of our friends in the technical press have been good enough to say some kind things with regard to the courage of our convictions. It did not take a very great deal of courage to do the right thing, and it cannot be denied that right principles should always govern.

Naturally, ten years of almost undivided attention to electrification work has brought a better knowledge as to how power-houses, lines, locomotives, and shops should be constructed, and I do not believe I overstate when I say that the electrical plant the New Haven now possesses could be reproduced, and with far better operating results, at certainly not more than 60 per cent of its original cost, but, notwithstanding this, when the electric division is on a 100 per cent electrical basis the economic return will be sufficient to justify the electrical expenditure to date.

The recent decision as to choice of system on the part of the Pennsylvania Railroad in favor of single phase for the proposed electrification on the main line between Philadelphia and Paoli, this action being a forecast of the system to be employed in the event of the future financial situation permitting electrification between New York and Washington, was one of no small consequence and pleasure to those who had been toiling to establish a correct application of electrification to trunk line territory.

To those who every day had been in close association with the practical workings of this system initially installed on the New Haven, failures were too closely associated with cause and effect to suggest even disappointment, to say nothing of discouragement, but let me refer to an admirable and fine distinction as evidenced in the decision of Gibbs and Hill, which discounted apparent for real results, and settled that the body of their electrification should be upon a single-phase basis, notwithstanding that the largest terminal upon the same railroad was operated upon a direct-current basis.

I envy, indeed, the result that they should be able to produce for the Pennsylvania Company in the use of straight alternating current upon their lines. Even the record of the New York, Westchester and Boston with its straight alternating equipment whose log sheet reports will show 125,000 miles per car failure, may be surpassed on the Paoli division by this coming Pennsylvania electrification. As I forecast this record that should be made, I review in retrospect some of the experiences that have caused it to be possible. Among the number are generator windings that have torn themselves loose from their housings by action of 11,000-volt short circuits upon their grounded phases; sectionalizing oil switches on the line hurling their cover plates 100 feet in the air, due to these same short circuits; the overhead contact line parting company with itself, due to high-speed pantograph shoes impinging themselves against the hard spots at hanger points; locomotives nosing their way along the tracks with broken quill springs and grounded motors; and so we might go on drawing the picture of our difficulties based upon lack of experience, but the future is the brighter picture. None of the railroads, not one, will have to go through this. It is all behind us, and present operating statistics are now the proof that the high-voltage alternating-current electrification, with its attendant higher efficiency, will be as reliable as the direct-current, if not more so, on account of the simplicity of its control.

Governed by the right principles, we have passed from the days in which we desire to make it work into those in which we must make it pay. Accurate distributions of the costs in all departments of construction in their application to power-house, lines, locomotives, and shops, together with expenses incident to the maintenance and operation of these salient features since the work was first undertaken, have shown a declining curve of unit costs throughout these various details as against the progress of time. Some road had to make the first break into the dark. No one had any advice to give, as no one had any experience upon which to base it. Some of our critics have been inclined to view the New Haven electrification as a great experiment. They are right—it was; but as an experiment it has given a cleaner and more reliable ride for the public, and in the end will not cost the New Haven road a (economic) penny; but its greatest value in my estimation has not been so much this as the more stable position in which it has placed the other roads to this country to consider electrification, a subject to which they will have to address themselves in the near future.

The larger part of the experimentation is over, and, from the data assembled, future results, in the application of electricity in heavy trunk line territory, can be predicated on assembled facts, and not predicted from hypothetical analysis. Critics have had it that the so-called "battle of systems" has delayed the electrification of railroads. As an electrical engineer keenly alive to the desirability of interesting railroads in moving their trains by electricity, I am glad if any insistence on my part upon the matter of "system first" has delayed electrification in this country, and argue that every minute of the delay will be a future asset to the railroads.

When we talk about railroads we generally mean trunk lines, and all trunk lines have essentially common and determining characteristics that make the best system of power distribution for one the best for all. Therefore I count it most fortunate that electrification has been delayed. Over the same standard gage, cars of every description can be hauled. Therefore, why not a standard overhead conductor, under which every form of electric motive power can operate?

I recall with interest one of the New York Railroad Club meetings, of which many have been held, typified as their "Electrical Night," at which a committee, previously appointed, reported its recommendations with regard to the application of alternating or direct current to specific situations. Particular stress in this report was laid on the advocacy of direct current for large terminals. This appeared to me as a fallacious conclusion, as the record of my remarks for that evening will doubtless disclose. It was clockwork typified in the movements made in these great New York Central and Pennsylvania direct-current terminal electrifications. A credit indeed was due the splendid corps of engineers who in those early days were responsible for the decision and execution of these works; yet conspicuous for their absence on this committee was that same corps of engineers, for to have subscribed to such an electrification policy would have included their concession that the tail of the dog was to wag his body! The committee made it clear that if the electrification was to be confined to terminal limits, then without question that electrification should be undertaken upon a direct-current basis. Immediately following this recommendation, alternating current was prescribed as best befitting trunk lines. I well recall the hiatus from which my brain reeled as I listened to the speaker divorce the trunk line from its terminal and draw in perpetuity the picture of the one great electrical evil from which it was desirable to escape; namely, the uncongenial marriage of alternating current to direct current. Fortunately we have learned enough about this matter by experience not to fear the execution of such a policy. As evidence of this fact, one of the simplest proofs is a reference to the wonderful reliability and economy of service to which we are treated in serving the great terminal yards at Oak Point and Harlem River with the straight alternating-current switching locomotive. During the past two years, in which 16 engines of this type have been in operation and in which over 1,000,000 locomotive-miles in commercial switching service have been recorded, there has been, as previously said, just one main motor failure. This however, is touching upon details of which we will speak later, and I have only mentioned it here in support of the argument that all motive power equipment should, if possible, be designed for operation upon one form of current, this being one of the essential conditions precedent to successful electrification.

At this juncture it is of interest to point to the fact that under the single-phase, high-potential contact wire, three types of electric motive power—the single-phase, the three-phase, and the direct-current (through the medium of a rectifier)—can operate; thus each class of equipment is permitted a supply of power unchanging in form.

The principle of cardinal importance to the writer's mind, and one of the conditions affecting the success of main line electrification, may, therefore, be said to be the establishment of a standard system of power distribution, from the contact wires of which shall be delivered power in standard and unchanging form, and, while all electric locomotives or multiple-unit equipment will primarily receive this power in identical form, it may thereafter be modified or transformed to conform to any type of alternating-current or direct-current equipment, which is in turn prescribed by the local conditions. Such a standardization would provide a single high-voltage contact wire running throughout an entire electrification zone upon which are impressed 11,000 volts of 25-cycle, single-phase electricity.

Such a line could have operating beneath it single-phase equipment of the New York, New Haven and Hartford design, three-phase equipment of the Norfolk and Western design, and, finally (through the medium of the rectifier), direct-current equipment of the New York Central design, all of these equipments having entirely dissimilar torque-speed characteristics prescibed as local conditions demand. I believe that we will all admit that such a standardization offers a wonderful flexibility, but, after all this, flexibility is not the real reason for its acceptance, although we cannot fail to class it as one of the facts that form a part of a correct conclusion. The real reasons are rooted in the field of economy, where the railroad dollar must justify its investment. There is no other distribution and contact system that can touch it in efficiency. Its principles have intertwined themselves with every application of electricity in the variegated field of its usefulness, and in no place is its application more apt than in supplying power for train movement.

Up to this point the writer has possibly levied upon your indulgence in treating his subject upon very general lines, but in so doing there has not been a moment when the specific subject of the paper has not been in mind. The subject itself is such a broad one that in truth it must be said that it has been more difficult to know what not rather than what so say, and what has been said has only been in an effort to show that during his pause we have been schooling ourselves by the analysis of the data secured; sorting it into cost *versus* return; studying comparative results arising under varying conditions; crystallizing out the mistakes that have been made in the past by lack of sufficient experience and information; drawing conclusions that are not guesses on what shall be the future methods to be followed in electrification, and assembling our facts for ready reference and application.

Now, coming to the specific subject of the paper, let me point first to the great underlying condition, apart from the engineering, construction, and operating side, upon which the success of main line electrification, from a combined public and railroad standpoint, is founded: success is entirely dependent upon the *density of traffic*.

A commercially successful electrification may be described as one which, through its agency, cuts the operating expenses of steam-operated territory it has replaced to a figure whereby the savings effected are of an amount sufficient to justify the investment made.

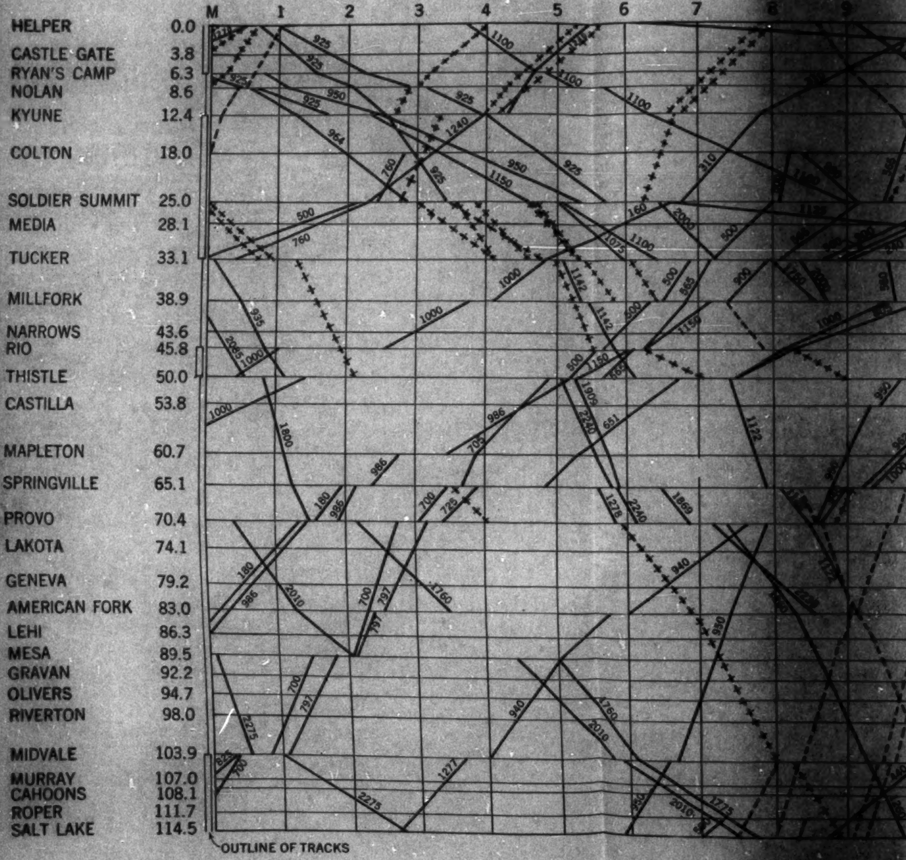
Our experience to date has taught us that electrification points to three principal places where economy of operation can be secured, and in the order of their importance they may be mentioned as follows:

1. Saving in fuel.

LEGEND

PASSENGER,------ FREIGHT, ——— LIGHT ENGINE+-+-+-+

NUMBERS SHOW TONNAGE HAULED



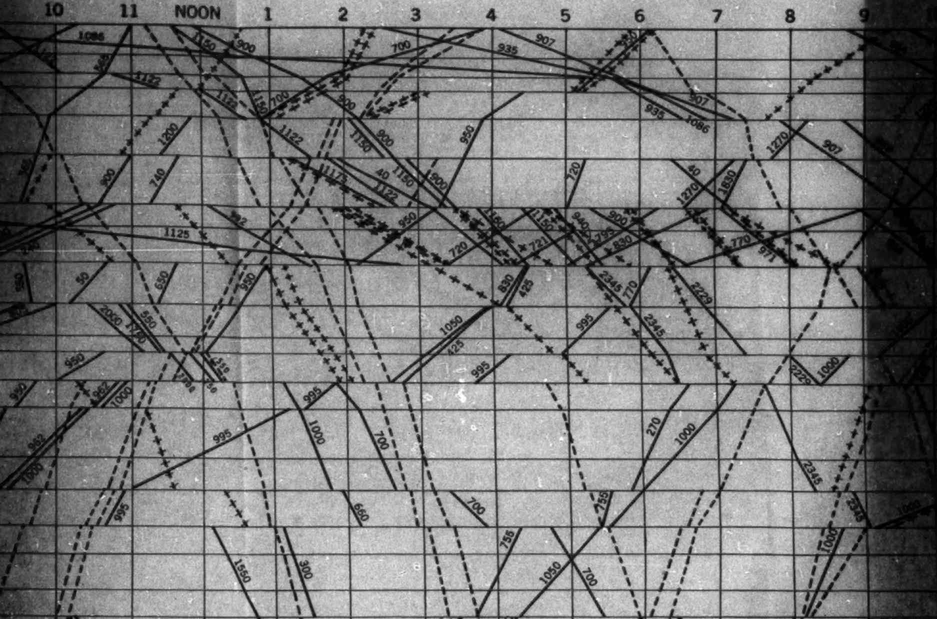
SALT LAKE DIVISION

TRAIN MOVEMENT

OCTOBER 17, 1912

TONNAGE OUT OF HELPER 10767. TONNAGE INTO HE

TONNAGE OUT OF SALT LAKE 8757. TONNAGE INTO SAL



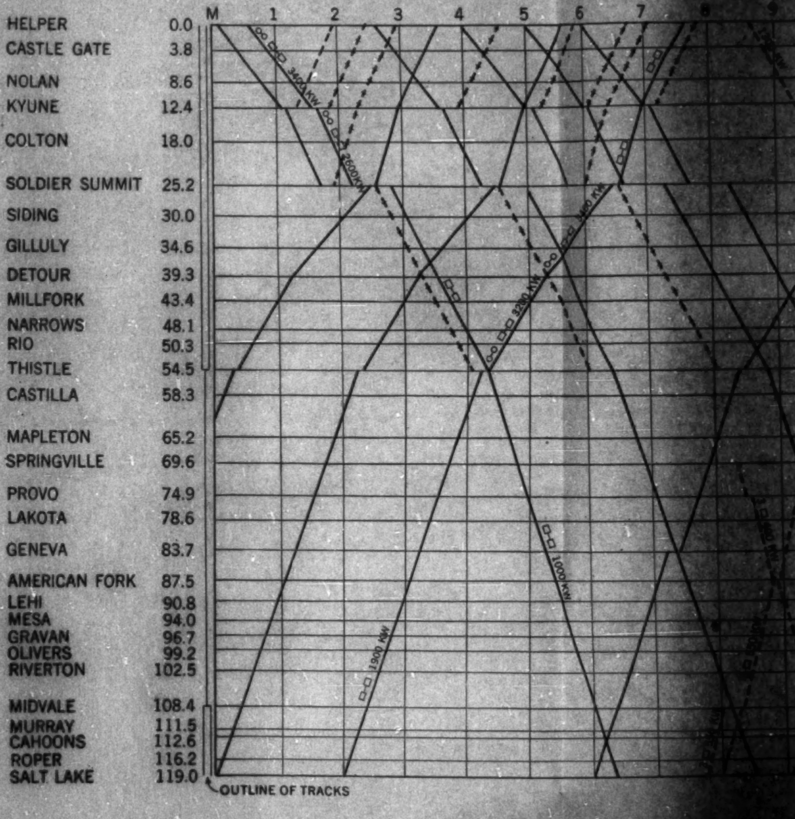
STEAM OPERATION

FIG. 7

KEY TO FREIGHT TRAIN MOVEMENTS

BETWEEN	WESTWARD				EASTWARD			
	NUMBER OF TRAINS	SPEED M.P.H.	TONS PER TRAIN	NUMBER OF LOCO.	NUMBER OF TRAINS	SPEED M.P.H.	TONS PER TRAIN	NUMBER OF LOCO.
HELPER - KYUNE	8	12.5	2,000.	○-○ □-□	5	20	1,800	□-□
KYUNE - SOLDIER SUMMIT	8	23	2,000	□-□	5	35	1,800	□-□
SOLDIER SUMMIT - DETOUR	5	20	3,000	□-□	5	14	1,800	○-○ □-□
DETOUR - THISTLE	5	20	3,000	□-□	5	17	1,800	○-○ □-□
THISTLE - SALT LAKE	5	35	3,000	□-□	5	31	1,800	□-□

FIG. 8; 204 IN



SALT LAKE DIVISION

TRAIN MOVEMENT

0% INCREASE IN TONNAGE OVER CHART OF OCTOBER 17,1912 (FIG.7)

LEGEND

— — PASSENGER, ———— FREIGHT, — - — - — LIGHT ENGINE

○ PUSHER LOCO. □ COMBINATION LOCO.

□-□ INDICATES TWO LOCO. OPERATED AS ONE UNIT

SMALL NUMBERS SHOW NUMBER OF COACHES

GENERAL DATA

TOTAL TONNAGE WESTWARD HELPER TO SOLDIER SUMMIT

TOTAL TONNAGE WESTWARD SOLDIER SUMMIT TO SALT LAKE

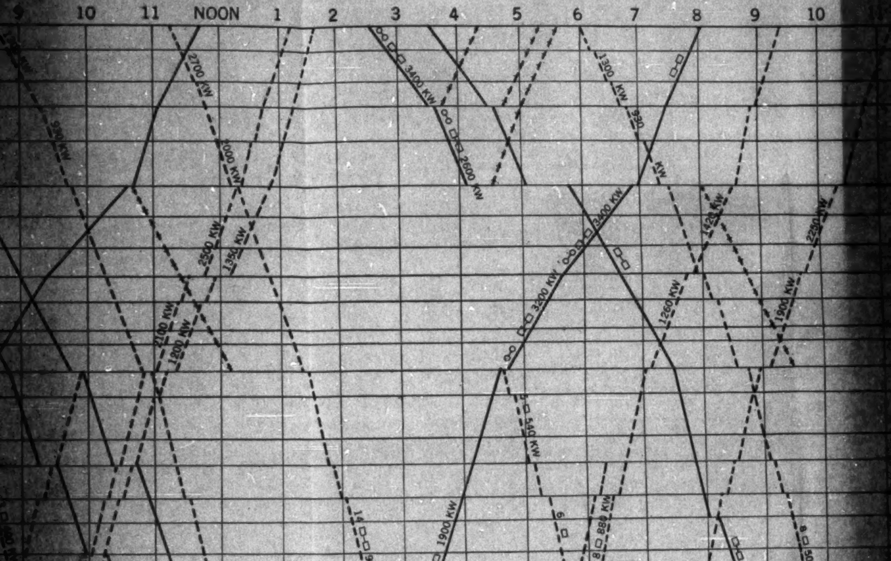
TOTAL TONNAGE EASTWARD SALT LAKE TO HELPER 9,000 TONS

TOTAL NUMBER OF PASSENGER COACHES WESTWARD 30

TOTAL NUMBER OF PASSENGER COACHES EASTWARD 36

TOTAL NUMBER OF TRAIN MILES WESTWARD 1217.2

TOTAL NUMBER OF TRAIN MILES EASTWARD 1141.6

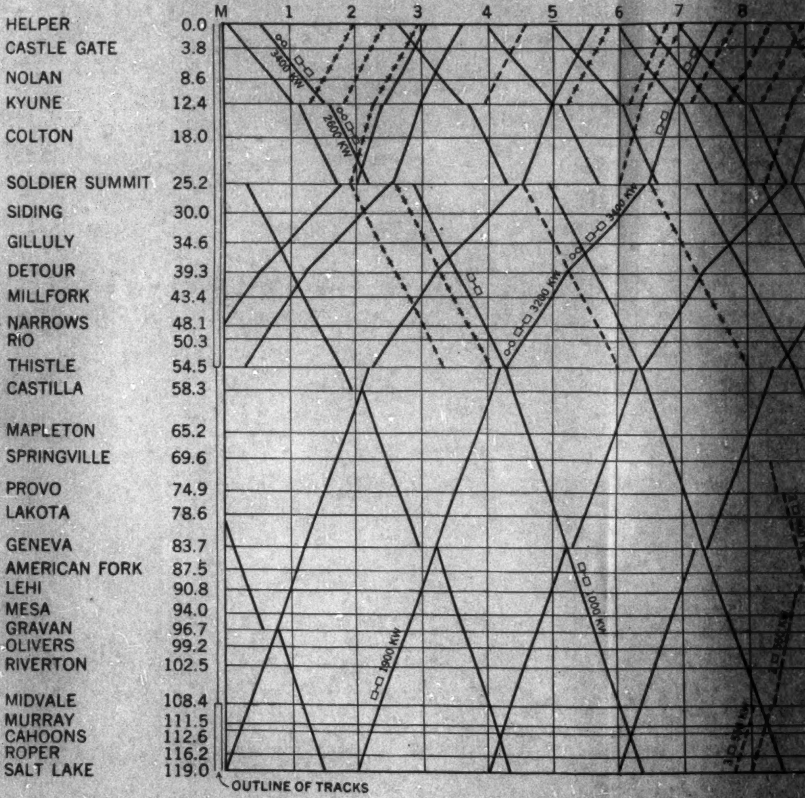


ELECTRIC OPERATION

FIG. 8

KEY TO FREIGHT TRAIN MOVEMENTS

BETWEEN	WESTWARD				EASTWARD			
	NUMBER OF TRAINS	SPEED M.P.H.	TONS PER TRAIN	NUMBER OF LOCO.	NUMBER OF TRAINS	SPEED M.P.H.	TONS PER TRAIN	NUMBER OF LOCO.
HELPER - KYUNE	15	12.5	2.000	○-○ □-□	10	20	1,800	□-□
KYUNE - SOLDIER SUMMIT	15	23	2.000	□-□	10	35	1,800	□-□
SOLDIER SUMMIT - DETOUR	10	20	3,000	□-□	10	14	1,800	○-○ □-□
DETOUR - THISTLE	10	20	3,000	□-□	10	17	1,800	○-○ □-□
THISTLE - SALT LAKE	10	35	3,000	□-□	10	31	1,800	□-□



SALT LAKE DIVISION

TRAIN MOVEMENT

FIG. 9; 100% INCREASE IN TONNAGE OVER CHART IN FIG. 8.

LEGEND

- - - - - PASSENGER, ——— FREIGHT, ➔ ➔ ➔ ➔ LIGHT ENGINE

○ PUSHER LOCO. □ COMBINATION LOCO

○○&□□ INDICATES TWO LOCO. OPERATED AS ONE UNIT

SMALL NUMBERS SHOW NUMBER OF COACHES

GENERAL DATA

TOTAL TONNAGE WESTWARD HELPER TO SALT LAKE 30,000 TONS DAILY

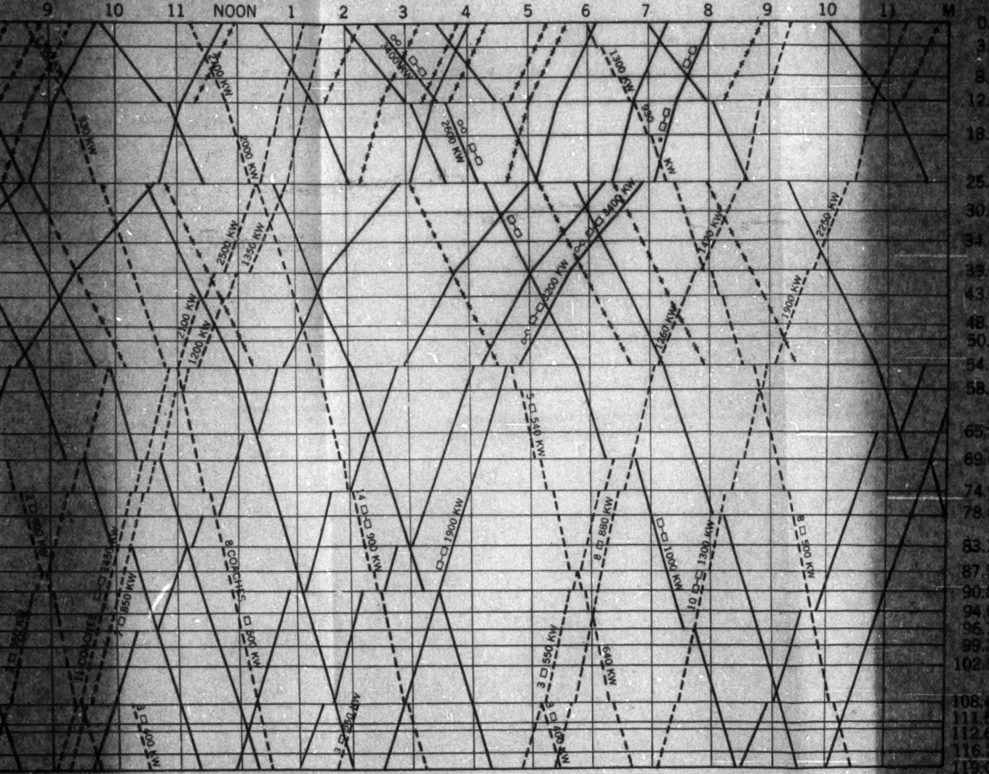
TOTAL TONNAGE EASTWARD SALT LAKE TO HELPER 18,000 TONS DAILY

TOTAL NUMBER OF PASSENGER COACHES WESTWARD 30

TOTAL NUMBER OF PASSENGER COACHES EASTWARD 36

TOTAL NUMBER OF TRAIN MILES WESTWARD 1862.6

TOTAL NUMBER OF TRAIN MILES EASTWARD 1736.6



ELECTRIC OPERATION

Fig. 9

[MURRAY]

2. Saving in motive-power maintenance and repairs.
3. Saving in train-miles.

Assets created by electrification, which may at times be controlling factors, as, for example, the reclamation of city terminal property, after the removal of gas and smoke by the elimination of steam locomotives, are of most important consideration. In cases, however, that do not involve large city terminal electrification, the general credits and debits resulting from electrification work may be said to about offset each other, and thus the value of the returns can be based upon the three items first mentioned. If we know the number of freight and passenger train-miles in a division proposed for electrification, and the cost of each one of the train-miles, today we can say with very little chance of error what the cost of each one of those train-miles in freight and passenger service will be when that division is operated by electricity. If we were to duplicate the steam train movement by an electric train movement a certain economy would be shown, but by reason of the ability to concentrate in single train movements greater tractive efforts and higher speeds, greater individual tonnages can be translated, and thus the third item of economy appears in the reduction of train-miles.

As bearing on the matter of a reduction in train-miles through means of electrification, the three charts (Figs. 7, 8 and 9) applying to studies recently made on the Salt Lake Division of the Denver and Rio Grande Railroad are interesting. In these charts it is of importance to note the great reduction in train movement secured by electrical operation, in combination with the reduction of a section of high grade from 4 per cent to 2 per cent for increases of 20 per cent and 100 per cent in excess of the former tonnage. The example offered is merely illustrative of this application of economy under conditions of electrification.

Experience with the movement of billions of ton-miles in freight, passenger, and switching service by electricity has justified the early predictions that were made in connection with the study of the New Haven electrification; namely, that one pound of coal burned under the boilers of a central electric power station and converted into electrical energy and transmitted to an electric engine will develop twice the drawbar pull at the same speed as a similar pound of coal burned in the firebox of a steam locomotive; and, second, that the maintenance and repairs on electric locomotives of the straight alternating-current type are on the order of one-half of those required for steam locomotives of equal weight on drivers. It is thus seen that the problem of electrification merely revolves around the question of the destiny of traffic in which the economies aforesaid can be practised, and, therefore, the denser the traffic the greater the requisite motive power for its movement, and hence the greater the saving to be effected. If the schedule of train movement for all roads were the same, then, based upon the number of tons translated, it would be a simple matter to plot a chart which would show two intersecting curves, one of which represented the savings per annum to be effected by the substitution of electricity for steam, the other the summated cost per annum of interest, depreciation, maintenance, insurance and taxes on the electrical plant, inclusive of power-house, lines, locomotives, and shops, necessary to effect these savings, these curves having as common abscissa tons under translation and as ordinates the annual costs respectively represented in the foregoing classes of annual expenditures. The point of intersection of these curves would indicate the density of traffic at which the economic yield of electrification would cover the fixed charges incident to its installation. The curves would also indicate the yield to the railroad that electrification would bring above that of steam operation for traffic densities of greater amount. The analysis, however, is not as simple as this, for, while a number of roads might translate equal tonnages over equal distances, the local conditions might require a wide variation as to schedule; also such physical adjuncts as grade and cost of electric power supply, labor and material clearly make it necessary to give careful consideration to each individual case. The point which I wish to make, however, is that, with knowledge based on experience, operating officials of railroad companies can have an intelligent presentation made to them of the comparative cost relation between steam and electric operation for these several roads. An intimate acquaintance with the ways and methods of the steam railroads of today has taught us how the president, the vice-president, the general manager, the general superintendent, the mechanical superintendent, the division superintendent, the master mechanics, the road foremen of engines, the shop superintendent, and so on down the line to the engineers whose hands are on the levers of either the steam or electric engines, look at operation. Seven years of parallel steam and electric operation on the same division have opened up a world of perspective to the writer, as he has studied the controlling forces which whirl through the beginnings of this conversion from steam to electricity in the trunk line territory of our American railways.

I would count it a serious omission indeed did I not mention the great and able assistance the present general manager of the New Haven Road, Mr. C. L. Bardo, has given in his study of the operating side of this great electrical problem. It is of him that I think when I touch upon one of the essentially real conditions affecting the success of main line electrification, and that is in the matter of administration. Electricity as an agent of power development is as essentially different from steam as the effects which are produced in the application of heat or cold. The steam locomotive has lived a useful life of eighty years. This is not a prediction that it will not live many more! Even in the clothes of its mechanical ruggedness it is not difficult to conceive of its having once been a pretty delicate machine, deserving of a very great deal of care and attention. The electric locomotive was born of even a more delicate nature, and, while its ruggedness is increasing, it can never possibly be the great mechanical brute that our high-powered steam locomotives may be typified as being today. In the same breath, however, it may be said that the steam locomotive can never reach into the zones of usefulness to which the electric engine can at the present day enter.

It is perfectly possible to keep the maintenance and repairs of the electric locomotive down to one-half of those of steam under the most favorable conditions of steam maintenance, and in many cases below this figure. On the other hand, due to the peculiar nature of the electric engine, which has not as yet been enough appreciated, it will be only by the most rigorous and careful inspection and conformity to rules of operation that this relation can be maintained. Indeed, if electric engines be treated as has been the custom of treating steam locomotives, then their repairs, instead of costing far less, will cost far more than those of the steam engine. The essential difference between the steam and the electric engine is that the former, after it has done all the work it is capable of doing, will lie down, simply stop going, and do this at no cost to its mechanical parts, while an electric engine, like an overwilling horse, if permitted, will work itself to destruction. The commercial life and efficiency of a steam engine may be said to depend on keeping the heat within its cylinder walls, while the commercial life and efficiency of the electric locomotive are based on how cool you can keep its conductors. In the vernacular of the American youth, some difference! Yet, if you should ask the old steam superintendent operating the new electric division if he agreed to that distinction, the chances are he would say: "Sure, the conductors should never get hot, especially with a passenger." Mr. Bardo has recognized this great difference between steam and electric operation, and in handling the schedule of electric trains he has emphasized the importance of keeping the train loads down to a point within the safe temperatures of the electric motors performing the schedule. The days are passing when with pride the steam operating man points to the electric locomotive as having been able to perform twice the duty for which it was designed, and the next day wonders why the darned old "electric" blew up on half the load. The point to be established, therefore, is that successful electrification requires that there be in the administrative forces minds trained to the necessity of a different viewpoint from that which has come down through these eighty years of steam service. The magnificent organization that has shaped itself throughout these many years and has standardized itself, one might say, in its application to all roads, need not in any way have its fabric torn or changed by the introduction of electricity as a motive power, but there must be established in the administrative forces different minds from those in the past to handle these different things of the future. The future must see well-developed electrical cells in minds of the vice-presidents, general managers, general superintendents, etc., down the line.

An inheritance by the New Haven of the old steam locomotive engineers for the operation of the electric engines is another case where the tail of the dog wags the body. While it is a good argument that these men understand the roadbed and signals better than any one else, this argument fails when engineers without electrical experience or training can bid in the electric runs, depending upon their seniority and record of service. The condition might be alleviated by one set of men, once in remaining in, but there is a constant change, and it is a long time before the steam locomotive engineer divorces himself from the fact that he is not operating a steam locomotive. During his period of learning how to operate the electric engine he does not suffer, the people do not suffer, but the road suffers, and the locomotive suffers most. Here, therefore, we see the necessity of electrically trained men. The very logic of this stand will ultimately require that these things be so, and one of the successes of which we write in this paper is based upon it being made so.

While all of the main line tracks of the New York division are electrified, there still remains in passenger and freight service, as previously shown, a considerable amount of steam operation, made necessary because the New Haven Road had to avoid capital expenditure for power house and motive power equipment. It can be readily understood that a large reduction in operating expense can be effected when the division is placed upon a 100 per cent electrical basis. On previous occasions when the writer has been dealing with statistics and information made available by his engineering and operating association with the work, he was conscious then, and is now, of the danger, in presenting construction and operating costs, of their possible misinterpretation.

Essentially necessary is a wholesome confidence on the part of railroads undertaking electrification that the result predicted will be attained, and what we are doing on the New Haven today electrically from an operating standpoint could not be better epitomized than by the presentation of one of the last monthly operating reports. The tables that follow comprise the statistics of electrical operation, and give operating information with reference to:

1. The amount, distribution and cost of electric power generated at Cos Cob Station.
2. Statistics and operating costs of electric passenger service.
3. Statistics and operating costs of electric freight service.
4. Statistics covering line and equipment failures.

These records are included in this paper not as an exhibit of something remarkable, but simply to convey to those interested in the electrification of railways the fact that there is daily coming to us a mass of data having reference to the practise of heavy electric transportation, through the agency of which very accurate conclusions may be drawn.

I would ask those who review these statistics with an analytical eye to bear in mind that they are taken from an electrical plant which, from its inception, has been handicapped both from a construction and operating point of view. As before explained, the underlying principle applying to the New Haven electrification required that its motive power equipment be designed to operate on both alternating-and direct-current power, and that, further, on account of inadequate shop facilities in the past it has been necessary, since securing new shop facilities, to make very heavy repairs throughout the entire electric motive power of the road. I have, therefore, to offer this word of caution in analyzing the statistics that are presented, for it is to be noted that the cost of locomotive repairs is high. For example, referring specifically to the table of operating costs of electric passenger engines, (Table XVIII), it is to be noted that in the month of October the repairs are recorded as 8.56 cents per locomotive-mile, while for November these repairs have increased to 10.61 cents per locomotive-mile. At the first blush this would indicate that the new shop facilities were increasing rather than diminishing maintenance costs. This, however, may be explained by the fact that all of the passenger engines have been undergoing general repairs, and invoices for material were passed in greater amounts for November than for October. Many of the electric locomotives have not received a general overhauling since 1907, and during this time their log sheets of operation show some of the locomotives have made over 350,000 miles.

Showing conclusively, however, what can be done with electrical equipment under the care of a better maintenance, I have taken the first ten engines that have received general repairs and present herewith in Tables I to X, inclusive, segregated monthly costs and mileages made since these engines have passed through the shops.

Notwithstanding these engines are of the alternating-current-direct-current type, it is of interest to note that their records so far show an average cost under five cents per locomotive-mile. It is of particular interest to note that locomotive No. 032, which received its overhaul first, has now operated 93,140 miles at an average cost of 3.6 cents per locomotive-mile.

These maintenance figures for the ten engines give a sharp contrast to those in the general table of passenger engine operating costs (Table XVIII) and emphasize the lack of maintenance to which the electric locomotives were subjected in the early days of their operation. Had conditions permitted our electric passenger engines to be of the straight-alternating-current design, in my opinion their average maintenance would not have exceeded 4 cents per locomotive-mile.

During the past six years of electric operation there have been collected some very valuable data with regard to the amount of power required to operate trains of variable tonnage in passenger, freight, and switching service. Based upon these data, the power required to operate trains under normal or peak conditions of schedule can be calculated with results practically coinciding with the estimates.

By means of wattmeters installed on all locomotives and motor cars it has been possible to record the differences of power required by trains operating under local and express conditions. The long period over which these statistics were kept and power rate constants thus developed has permitted us to abandon an elaborate tabulation and conslidate the information in the more general statement (Tables XVIII and XIX). Of value to those who are interested to follow more closely these results, Tables XI, XII, and XIII will be of assistance. These tables are compiled from the June, 1914, statistics of electric passenger and freight train operation between Woodlawn and points east to New Haven. At that time the overhead system had only recently been completed to New Haven, and there was but a a small percentage of electric service, both as regards passenger and freight, between Woodlawn and New Haven, and, while the tonnage in both passenger and freight service has been greatly increased since that time, these tables, however, may be taken as giving reliable data in connection with the electric train movements recorded. The watt-hours per ton-mile are secured through meters recording input power to the electric motors. To determine the actual amount of power taken from the contact wire, these figures should be divided by 97 per cent, thus allowing an average loss of 3 per cent for the step-down transformers installed on the electric engines and motive power. As examples of the increments of electric service, since the extension of the electrification to New Haven, while it is to be noted that the total electric passenger ton-miles for June, 1914, were approximately 41,000,000 and that of the freight 9,400,000, the former has now increased to 62,000,000 and the latter to 44,000,000.

Of especial interest to the writer with regard to the tables covering electric passenger operation is the variation in watt-hours per ton-mile for the various express and local services. For example, it is to be noted that the power rate for New Haven express trains eastbound is 31.4 watt-hours per ton-mile, this rate being increased slightly for trains operating to Stamford; the rate rises quite rapidly for trains operating in local service to

Stamford, and continues to rise for local trains operating to Port Chester and New Rochelle respectively. It is, of course, well known that the rate of power supply per ton for express operation is very much lower than that required for local operation, as in the case of the latter the train suffers, under the conditions of braking, the loss of the kinetic energy stored in it under the conditions of acceleration. The increasing watt-hours per ton-mile as shown in the tables are practically proportional to the diminishing distance between train stops. It may also be said that the distance between stops increases progressively east of New York City, and if, for example, suburban territory under consideration for electrification has to be served by train schedule with distances between stations approximately the same as those obtaining on the New Haven Road, the " power rate " constants as shown in these tables will be found to be sufficiently accurate in the study of power necessary to train movement.

In the tabulated statistics covering electric freight operation the point of principal interest is the difference between the rate per ton-mile as indicated in the June tabulation (Table XIII) as against those shown under the general tabulation of freight service (Table XIX), where it is to be noted that the kilowatt-hours for fast and slow freight are, on the average, considerably below 30 watt-hours per ton-mile, this rate being based upon the tonnage of the trailing load. Allowing for the weight of the electric engine, the watt-hours per ton-mile will be reduced to 26, and, as some 200,000,000 ton-miles have been actually recorded by meter registration in freight service, it may be said that 30 watt-hours per ton-mile on level track is a reliable figure, with slight margin to cover electric freight operation in a combination of fast and slow service, *i.e.*, without stops for trains averaging between 1500 and 3000 tons trailing load.

It is of interest at this juncture to point to an interesting experience we have had in connection with the electrical operation of heavy freight trains. It was first thought that when these large train units were placed on the line the power-house would be subjected to very heavy drafts of power under conditions of accelerating them. The reverse, however, was found to be the case, and where, previous to the operation of these trains, the power station output curve showed peaks of a fluctuating character, these heavy trains have served to smooth out the curve of power station output. A reasonable explanation of this would seem to rest in the fact that when a number of the heavy trains are under translation, and it becomes necessary to accelerate one from rest, the supply of current necessary to this acceleration, while not reducing the line voltage materially, does so, however, to a point which corresponds to a speed of the trains in translation lower than the speed at which they are actually operating, and thus these heavy trains, by their own mass energy, as in the case of a flywheel, automatically release a large amount of power, which becomes available for the accelerating train.

In the foregoing pages I have confined myself to the presentation of operating data, from which I believe very accurate conclusions can be drawn, having regard to the costs incident to electric operation, the only expenses that are materially changed in the conduct of railway transportation being, as previously stated, in the matter of fuel, engine repairs, and train-miles. With definite information developed as to these items, it is not a difficult matter for those experienced in their application to interpolate them into the steam operating accounts in the study of railroads considering electrification. I have thought, therefore, that the broader manner of handling this subject would be not to show concrete cases where the conditions were such as to insure the success of electrification, but rather present the constants of economy that were generally applicable, at least very approximately so, to all railway situations, granting of course, that each individual study would have its qualifying factors which local conditions would control; as, for example, it is quite possible for a complete electrification to turn upon the cost of coal. The greater the cost of coal the stronger is the argument for electrification, from the fuel aspect. For example, if two railroads, one burning $2.50 coal and the other burning $5 coal, should electrify, and in each case reduce their coal consumption by 100,000 tons per year, they would respectively save $250,000 and $500,000 per annum. In the case of the railroad burning the $2.50 coal this saving would, at 5 per cent, represent capitalized values amounting to $5,000,000, while in the case of the railroad burning the $5 coal the capitalized values would be $10,000,000. In both cases the capitalized values should be credited against the construction account for electrification.

Savings to be effected in engine repairs are likewise subject to local conditions, for, while it may be said that steam locomotives repairs, upon an average, may be placed at 10 cents per locomotive-mile, on the other hand there may be situations where the railroad has, for example, to use water of severe scaling characteristics and thus run up the cost of repairs excessively.

In the matter of train-miles the savings to be effected are dependent upon local conditions, but it can be stated as a general conclusion, based on a very considerable experience, that:

1. Electric engines on the order of 100 tons on drivers should be maintained at a rate not exceeding 5 cents per locomotive-mile.

2. The coal bill for transportation is cut to at least one-half.

Having determined for any situation what savings can be effected by the substitution of electricity for steam, then, as previously stated, the commercial justification of a change to the new motive power is entirely based upon whether these savings will cover the interest, insurance, depreciation, and taxes on the electrical investment necessary.

In past papers I have refrained from presenting construction costs to show what investment is necessary to operate trunk line territory by electricity, and I believe that this policy will be accepted as having been justified when I state that an analysis of the distribution account of our latest line construction (between Stamford and New Haven) shows its unit costs (four-track) to have been one-half those incurred in the original work, and, while further economies will, of course, follow, I feel that the curve of decreasing electrical investment for electrification has flattened at least enough to present Tables XIV, XV and XVI, indicating the costs incident to six-track, four-track, two-track, compound and single catenary, for curves and tangent construction, as a guide to what can be done. To those considering these figures I would offer a word of suggestion that the overhead system of the New Haven Road was designed to coordinate with a road bed which is the throat of the entire eastern New England traffic. Very high safety factors have been included in it, both as regards wire and steel, and it has been many times, particularly during the last season, subjected to high wind velocities, the effects of which have been augmented to ice formation, increasing its projected area.

A general factor of safety of three is prevalent throughout the whole construction, whether on the 200-ft. river transmission towers with 800-ft. spans or on the regular catenary construction, in each instance based on ice coatings of ½ inch all around with wind velocity of 60 miles an hour. I might add, also, that we have been fortunate enough not to have lost a wire due to the above causes throughout the history of the electrification.

Briefly referring to the tables of construction costs, it is to be noted that the supporting steel bridges have a normal spacing of 300-ft., the trusses of which are designed to withstand the breakage of any of the main supporting messenger wires, and permit also the support at any point of four signals of 2000 lb. in weight each.

As local conditions make different requirements for sectionalization, construction costs are given for continuous catenary construction for tangent and curved track, and, to facilitate the introduction of sectionalizing costs, individual figures for anchor bridge and control sectionalization are given under tables showing costs varying for the different number of tracks under consideration.

Electrification, like everything else, under effects of standardization gets down to a pound or foot basis; the costs tabulated for the different types of construction sectionalization and control may be combined to determine total estimates on work conforming to the requirements of the local conditions.

With regard to electric motive power equipment, papers that have preceded this one have discussed in detail physical dimension, weight, and operating characteristics of electric passenger, freight and switching engines and multiple-unit motor cars. The motive power feature of electrification, like its other parts, has virtually reached the pound stage. Electric locomotives of approximately 100 tons will under present conditions of cost of labor and material, vary between 18 cents and 20 cents per pound. This figure is practically irrespective of speed-torque characteristics, a high-speed passenger locomotive and a low-speed switcher not varying greatly in cost upon a pound basis. Multiple-unit cars, now usually built of steel, do not vary greatly from the above figures, but, if anything, may be quoted as being slightly higher in cost per pound.

The determining characteristics of the locomotives to be purchased in an electrification will, of course, entirely depend upon the local conditions which control the maximum and continuous tractive efforts in passenger and freight service, they in turn depending upon the weight of trains and length of grades, capacity of equipment depending likewise on the two foregoing factors and schedule requirements.

The above approximate quotations on engine costs are presented merely to give a general idea of this department of expense in connection with electrification. As a concrete example in application of the above general statements, I would say that a first-class, high speed, 100-ton, straight alternating-current electric passenger locomotive, capable of handling a 250-ton trailing load in normal large city suburban service, should cost $40,000. A steam locomotive which would do the same work would probably not cost more than $15,000, but the savings effected, due to the greater operating economy of the electric engine, would represent a figure of twice or three times the amount invested in the electric engine. Thus we might say that for every electric engine we purchase we would be justified at least in making a capital investment of $40,000 to cover the cost of electric power-houses and transmission equipment necessary to supply that electric engine with current. By this reasoning we again approach the answer as to the conditions affecting the success of main line electrification in the fact that it is the density of traffic and in the use of a large number of electric engines by which we can save enough money to pay for the capital expenditure necessary to the supply of power to them for the operation of many trains.

Of late many interesting and valuable papers on electrification have been written, wherein the authors have presented comparable data as between steam and electric operation on specific territory under contemplation.

As mentioned in the earlier pages of the paper, there are many places where electrification would bring a betterment both to the public and to the railroad, but the writer has thought the subject would be better served by a general exposition of his operating and construction experience in connection with a heavy trunk line electrification that has been serving the public for the past eight years, and to draw from it the significant facts and factors from which basic conclusions can be drawn to apply elsewhere.

In concluding the paper I would plead for an especially conservative point of view on the part of the public with regard to electrification. While the savings to be effected under certain conditions of electrification may be considerable, on the other hand the construction investment necessary to these savings may be very great. So many roads in this country have either passed or lowered their dividends, the chief example being a part of the great Pennsylvania system, that it is hardly necessary to emphasize the fact that only a healthy condition of finance throughout the country will warrant the consideration of electrification, and again I would say that partial electrification, such as that applying to yards only and not main line, while it might prove of advantage to a public, might at the same time prove to be a serious and unfair burden for the railroad to carry.

The Public Service Commissions are as much the guardians of the railroads as the people they serve, and the many billions in dollars representing the shrinkage in value of railroad securities in the last few years have awakened in the hearts and minds of the public and the commissioners the fact that no further obligations can be imposed upon the railroads, except they be justified from a fair railroad business standpoint, such equity of treatment describing the duty of the commissioners in whose hands rests the justice of any demand. The electrification of great railroad terminals in particular presents conditions in which the maximum cost is combined with the minimum direct return upon the invested capital, and without some reasonable assurance of adequate return it will be more difficult to secure the necessary capital for such improvements.

TABLE I

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 032.

	1913					
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Labor	32.90	83.01	61.59	23.67	20.18	89.17
Material	20.68	38.61	67.96	21.64	34.56	104.86
Total labor and material	53.58	121.62	129.55	45.31	54.74	194.03
Mileage	4,802	5,517	4,695	4,716	4,687	4,592
Cost per mile	0.011	0.022	0.028	0.010	0.012	0.042
Average cost per mile	0.011	0.017	0.020	0.018	0.017	0.021
Total miles to date	4,802	10,319	15,014	19,730	24,418	29,005
	1914					
	Jan.	Feb.	Mar.	April	May	June
Labor	200.97	85.94	36.52	65.42	91.01	70.70
Material	95.79	27.12	29.15	32.57	70.01	90.28
Total labor and material	296.76	113.06	65.67	97.99	161.02	160.98
Mileage	4,392	6,017	5,310	5,270	5,889	5,839
Cost per mile	0.068	0.019	0.012	0.019	0.027	0.028
Average cost per mile	0.027	0.026	0.024	0.024	0.024	0.024
Total miles to date	33,397	39,414	44,724	49,995	55,884	61,723
	1914					
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Labor	212.36	74.45	147.53	219.47	55.25	....
Material	131.49	156.72	173.96	780.92	146.09*	....
Total labor and material	343.85	231.17	321.49	1000.39	90.84*	....
Mileage	6,165	7,401	5,459	5,678	6,714	....
Cost per mile	0.056	0.031	0.058	0.176	0	....
Average cost per mile	0.027	0.027	0.030	0.039	0.036	....
Total miles to date	67,888	75,289	80,748	86,426	93,140	....

NOTE.—Cost in dollars. * Cr.

TABLE II

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 041.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	17.15	72.04	169.91	113.51	105.56	195.78
Material	8.92	78.24	362.15	288.68	32.29*	473.13
Total labor and material	26.07	150.28	532.06	402.19	73.27	668.91
Mileage	2,912	7,974	8,031	5,990	6,096	5,965
Cost per mile	0.009	0.018	0.066	0.067	0.012	0.112
Average cost per mile	0.009	0.016	0.037	0.044	0.038	0.050
Total miles to date	2,912	10,886	18,917	24,907	31,003	36,968

NOTE.—Cost in dollars. * Cr.

TABLE III

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 037.

	1914							
	April	May	June	July	Aug.	Sept.	Oct.	Nov.
Labor	35.93	61.68	72.78	93.79	119.65	107.20	75.63	115.50
Material	4.69	35.94	159.83	102.73	212.87	184.26	209.81*	47.34
Total labor and material	40.62	97.62	232.61	196.52	332.52	291.46	134.18*	162.84
Mileage	538	4,020	5,641	7,643	8,341	7,203	7,217	6,367
Cost per mile	0.075	0.024	0.041	0.026	0.040	0.040	0	0.026
Average cost per mile	0.075	0.030	0.036	0.032	0.034	0.036	0.026	0.026
Total miles to date	538	4,558	10,199	17,842	26,183	33,386	40,603	46,970

NOTE.—Cost in dollars. * Cr.

TABLE IV

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 028.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	2.04	63.12	135.80	119.00	259.41	78.35
Material	17.25	25.15	211.95	221.73	159.11	39.25
Total labor and material	19.29	88.27	347.75	340.73	418.52	117.60
Mileage	2,103	3,902	6,788	5,398	6,526	8,256
Cost per mile	0.009	0.023	0.051	0.063	0.064	0.014
Average cost per mile	0.009	0.018	0.036	0.044	0.049	0.040
Total miles to date	2,103	6,006	12,794	18,192	24,718	32,974

NOTE.—Cost in dollars.

TABLE V

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 020.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	50.54	148.29	129.71	120.20	127.45	76.35
Material	29.84	30.19	64.29*	195.31	55.41	248.09
Total labor and material	80.38	178.48	65.42	315.51	182.86	324.44
Mileage	5,391	7,997	8,175	7,227	6,664	6,348
Cost per mile	0.015	0.022	0.008	0.043	0.027	0.051
Average cost per mile	0.015	0.019	0.015	0.022	0.023	0.027
Total miles to date	5,391	13,388	21,563	28,790	35,454	41,802

NOTE.—Cost in dollars. * Cr.

TABLE VI

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 016.

	1913	1914				
	Dec.	Jan.	Feb.	March	April	May
Labor	23.52	71.03	108.88	78.80	132.74	106.13
Material	52.16	46.61	55.88	29.91	77.26	51.72
Total labor and material	75.68	117.64	164.76	108.71	210.00	157.85
Mileage	3,260	4,820.5	5,300	5,139.5	4,868	4,222
Cost per mile	0.023	0.024	0.031	0.021	0.043	0.037
Average cost per mile	0.023	0.024	0.027	0.025	0.029	0.030
Total miles to date	3,260	8,080.5	13,380.5	18,520	23,388	27,610

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	155.66	93.52	112.85	129.38	108.75	221.59
Material	179.80	91.61	152.97	21.28	64.64	13.86*
Total labor and material	335.46	185.13	265.82	150.66	173.39	207.73
Mileage	4,347.5	8,282	8,386	5,644	8,096	5,236
Cost per mile	0.077	0.022	0.032	0.027	0.021	0.040
Average cost per mile	0.037	0.033	0.033	0.033	0.031	0.032
Total miles to date	31,957.5	40,239.5	48,625.5	54,269.5	62,365.5	67,601.5

NOTE.—Cost in dollars. * Cr.

TABLE VII

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 01.

	1914					
	June	July	Aug.	Sept.	Oct.	Nov.
Labor	0	96.38	156.60	175.30	133.64	81.76
Material	0	285.76	351.57	312.04	84.85	15.03*
Total labor and material	0	382.14	508.17	487.34	218.49	66.73
Mileage	571	7,183	7,396	6,006	5,812	6,842
Cost per mile	0	0.053	0.069	0.081	0.038	0.010
Average cost per mile	0	0.049	0.059	0.065	0.059	0.049
Total miles to date	571	7,754	15,150	21,156	26,968	33,810

NOTE.—Cost in dollars. * Cr.

TABLE VIII

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 019.

	1914				
	July	August	Sept.	Oct.	Nov.
Labor	22.07	121.75	84.22	145.20	110.45
Material	4.18	406.70	207.84	129.73	317.68
Total labor and material	26.25	528.45	292.06	274.93	428.13
Mileage	2,886	7,894	7,766	6,938	5,056
Cost per mile	0.009	0.067	0.039	0.040	0.084
Average cost per mile	0.009	0.051	0.046	0.044	0.051
Total miles to date	2,886	10,780	18,546	25,484	30,540

NOTE.—Cost in dollars.

TABLE IX

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 05.

	1914						
	May	June	July	Aug.	Sept.	Oct.	Nov.
Labor	29.82	109.64	43 .55	117.45	113.10	235.34	88.80
Material	83.60	71.29	30.86	309.76	148.05	322.91	129.96
Total labor and material	113.42	180.93	74.41	427.21	261.15	558.25	218.76
Mileage	2,268	5,432	7,937	8,566	5,497	6,783	6,578
Cost per mile	0.05	0.033	0.009	0.050	0.047	0.082	0.033
Average cost per mile	0.05	0.038	0.024	0.032	0.036	0.044	0.043
Total miles to date	2,268	7,705	15 ,637	24,203	29,700	36,483	43,061

NOTE.—Cost in dollars.

TABLE X

PERFORMANCE OF N. Y., N. H. AND H. R. R. ELECTRIC PASSENGER LOCOMOTIVE 011.

	1914						
	May	June	July	Aug.	Sept.	Oct.	Nov.
Labor	34.55	43.59	145.87	114.21	211.08	74.86	166.71
Material	61.61	18.69	85.08	230.08	316.83	128.33	70.75
Total labor and material	96.16	62.28	230.95	344.29	527.91	203.19	237.46
Mileage	1,017	5,671	6,243	6,837	6,078	8,122	5,690
Cost per mile	0.094	0.011	0.037	0.050	0.087	0.025	0.042
Average cost per mile	0.094	0.023	0.030	0.037	0.049	0.043	0.043
Total miles to date	1,017	6,688	12,931	19,768	25,846	33,968	39,658

Note.—Cost in dollars.

TABLE XI.

STATISTICS COVERING ELECTRIC PASSENGER MOVEMENT AND "POWER RATE" CONSTANTS FOR DIFFERENT SERVICES—EASTBOUND.

	New Haven express trains	Stamford express	Stamford local	Port Chester trains	New Rochelle trains	Total
Number of trains	52	901	667	185	2	1,807
Number of locomotives	84	1,407	859	214	2	2,566
Number of cars	497	7,054	3,875	1,000	10	12,436
Tonnage	35,625	566,033	279,904	67,884	619	950,065
Train-miles	3,120	18,921	14,003	2,405	8	38,457
Locomotive-miles	5,048	30,954	18,894	2,889	8	57,793
Car-miles	29,304	148,134	80,263	13,000	40	270,741
Ton-miles	2,108,700	11,886,253	5,832,923	882,492	2,456	20,712,824
Kw-hr. used	66,076	405,835	343,846	58,933	222	874,912
Watt-hr. per ton-mile	31.4	34.2	59.0	66.7	90.2	42.2

Stamford local trains include one train, New Rochelle to Stamford.

TABLE XII.

STATISTICS COVERING ELECTRIC PASSENGER MOVEMENT AND "POWER RATE" CONSTANTS FOR DIFFERENT SERVICES—WESTBOUND.

	New Haven express trains	Stamford express	Stamford local	Port Chester trains	New Rochelle trains	Total
Number of trains........	49	958	604	185	0	1,796
Number of locomotives...	78	1,502	791	185	......	2,556
Number of cars..........	434	6,994	3,941	972	......	12,341
Tonnage................	31,963	574,569	261,202	62,559	......	930,293
Train-miles.............	2,940	20,118	12,684	2,405	......	38,147
Locomotive-miles........	4,620.5	33,044	17,402	2,497.5	......	57,564
Car-miles...............	24,855.5	146,870	81,676	12,591	......	265,992.5
Ton-miles...............	1,899,957	12,065,689	5,441,943	811,539	......	20,219,128
Kw-hr. used.............	60,900	486,203	346,935	62,734	......	956,772
Watt-hr. per ton-mile.....	32.0	40.3	63.7	77.3	......	47.4

TABLE XIII.

STATISTICS COVERING ELECTRIC FREIGHT MOVEMENT AND "POWER RATE" CONSTANTS FOR EASTBOUND AND WESTBOUND SERVICE.

	Eastbound	Westbound	Total
Number of trains..............	109	116	225
Number of locomotives.........	109	117	226
Number of cars................	2,939	2,829	5,768
Tonnage......................	106,905	86,706	193,611
Train-miles..................	5,273	5,564	10,837
Locomotive-miles..............	5,486	5,784	11,270
Car-miles.....................	142,542	135,792	278,334
Ton-miles.....................	5,184,893	4,161,888	9,346,781
Kw-hr. used...................	170,259	137,048	307,307
Watt-hr. per ton-mile..........	32.8	33.0	32.9

TABLE XIV.
COST FOR CATENARY CONSTRUCTION

6-track compound catenary	Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-0′ 300-ft. span	Curve 2°-1′ to 3°-0′ 300-ft. span	Curve 3°-1′ to 4°-0′ 260 ft. span with pull-off
Steel..................	$14,390	$17,810	$19,600	$23,480	$27,500
Concrete..............	4,920	5,640	6,330	7,600	10,600
Catenary material.....	16,650	16,650	16,650	16,650	17,910
Catenary labor........	2,800	2,900	2,900	2,900	3,220
Total............	$38,760	$43,000	$45,480	$50,630	$59,230

4-track compound catenary	Tangent 300-ft. span	Curve 0°-1′ to 1°-15′ 300-ft. span	Curve 1°-16′ to 2°-15′ 300-ft. span	Curve 2°-16′ to 3°-1′ 260-ft. span	Curve 3°-1′ to 4°-45′ 260-ft. span with pull-off pole
Steel..................	$9,350	$11,530	$13,280	$15,800	$18,850
Concrete..............	3,110	2,890	4,080	4,700	7,640
Catenary material.....	11,050	11,050	11,050	11,360	12,060
Catenary labor........	1,980	2,080	2,080	2,080	2,390
Total............	$25,490	$27,550	$30,490	$33,940	$40,940

2-track compound catenary	Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft.span	Curve 1°-1′ to 2°-30′ 300-ft.span	Curve 2°-31′ to 2°-30′ 260-ft.span	Curve 3°-31′ to 4°-0′ 200-ft.span	Over 4°-1′ curve 200-ft. span with pull-off pole
Steel.............	$6,900	$7,220	$7,830	$9,030	11,400	$16,160
Concrete.........	3,580	3,580	4,280	4,910	6,380	10,300
Catenary material	5,580	5,580	5,580	5,680	5,870	6,520
Catenary labor...	1,130	1,230	1,230	1,300	1,310	1,410
Total........	$17,190	$17,610	$18,920	$20,920	$24,960	$34,450

2-track single catenary	Tangent and curves up to 2°-30′ 300-ft. span	Curve 2°-31′ to 3°-31′ 260-ft. span	Curve 3°-31′ to 4°-30′ 200-ft. span	Curves above 4°-30′ with pull-off pole 200-ft. span
Steel..................	$6,680	$7,700	10,500	$14,900
Concrete..............	3,000	3,300	4,600	4,300
Catenary material.....	3,530	3,600	37,60	9,000
Catenary labor........	510	510	525	650
Total............	$13,720	$15,110	$19,385	$28,850

TABLE XV.

COST FOR CATENARY CONSTRUCTION.

Cost for One Mile Single Track of a Six-Track Road Compound Catenary.

Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-0′ 300-ft. span	Curve 2°-1′ to 3°-0′ 300-ft. span	Curve 3°-1′ to 4°-0′ 260-ft. span with pull-off pole
$6,460.00	$7,166.60	$7,580.00	$8,438.60	$9,870.00

Cost of One Mile Single Track of a Four Track Road Compound Catenary.

Tangent 300-ft. span	Curve 0°-1′ to 1°-15′ 300-ft. span	Curve 1°-16′ to 2°-15′ 300-ft. span	Curve 2°-16′ to 3°-0′ 260-ft. span	Curve 3°-1′ to 4°-45′ 260-ft. span with pull-off
$6,372.50	$6,887.50	$7,622.50	$8,485.00	$10,235.00

Cost of One Mile Single Track of a Two-Track Road Compound Catenary.

Tangent 300-ft. span	Curve 0°-1′ to 1°-0′ 300-ft. span	Curve 1°-1′ to 2°-30′ 300-ft. span	Curve 2°-31′ to4°-1′ 260-ft. apan	Curve 3°-31′ to 4°-1′ 200-ft. span	Curve over 4°-1′ 200-span with pull-of pole
$8,595	$8,805	$9,460	$10,460	$12,480	$17,225

Cost for One Mile Single Track of a Two Track Road Single Catenary.

Tangent and curves up to 2°-30′, 300-ft. span	Curve 2°-31′ to 3°-30′ 260-ft. span	Curve 3°-31′ to 4°-30′ 200-ft span	Curves above 4°-30′ with pull-off pole.
$6,860	$7,555	$9,692	$14,425

Cost for an Anchor—and Sectionalizing—Bridge.

	Compound catenary			Single catenary 2 track
	6 track	4 track	2 track	
Steel	$3,200	$1,600	$900	$620
Concrete	2,000	1,270	960	700
Floor on upper deck of bridge	200	160	100	100
Control apparatus and connections	8,000	6,300	4,500	4,500
Sectionalizing	600	400	200	200
Total	$14,000	$9,730	$6,660	$6,120

TABLE XVI.
COST FOR CATENARY CONSTRUCTION.

One mile of four-track single catenary	Tangent 300-ft. span	Curve up to 2°-0′ 300-ft. span	Curve 2°-1′ to 3°-0′ 260-ft. span	Curve 3°-1′ to 4°-0′ 200-ft. span	Curve above 4°-1′ 200-ft. span with pull-off
Steel	$8,800.00	$11,830.00	$13,490.00	$17,500.00	$20,500.00
Concrete	2,930.00	3,940.00	4,200.00	5,640.00	8,640.00
Catenary material	7,035.00	7,193.40	7,260.00	7,415.00	8,170.00
Catenary labor	1,237.60	1,311.50	1,320.00	1,339.00	1,540.00
Total	$20.002.60	$24,274.90	$26,270.00	$31,894.00	$38,850.00

One mile of single track of a 4-track road	Tangent 300-ft. span	Curve up to 2°-1′ 300-ft. span	Curve 2°-1′ to 3°-0′ 260-ft. span	Curve 3°-1′ to 4°-0′ 200-ft. span	Curve above 4°-1′ 200-ft. span with pull-off
Single catenary	$5,000.15	$6,068.74	$6,567.50	$7,973.50	$9,712.50

Anchor and sectionalizing bridge for four-track single catenary.	Steel	$1,200.00
	Concrete	960.00
	Floor on upper deck of bridge	160.00
	Control apparatus and connections	6,300.00
	Sectionalizing	400.00
	Total	$9,020.00

TABLE XVII.

THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD COMPANY. STATISTICS OF ELECTRICAL OPERATION—NEW YORK AND SHORE LINE DIVISIONS. FOR THE MONTH OF NOVEMBER, 1914, COMPARED WITH THE MONTH OF OCTOBER, 1914.

Cos Cob Power House.

	November		October	
	Total	Per kw-hr.	Total	Per kw-hr.
Coal consumed (tons)	12,439.44	2.78 lb.	12,280.84	2.75 lb.
Water consumed (gals)	38,778,000	4.33 gal.	35,835,000*	4.01 gal.*
Cost of coal	34,084.07	0.381 cent	33,526.69	0.375 cent.
Cost of water	1,582.15	0.017	5,015.55*	0.057*
Cost of other supplies	317.20	0.004	655.85	0.007
Maintenance of power plant and machinery	3,655.27	0.041	3,434.87	0.038
Wages and salaries	6,056.62	0.068	6,704.00	0.075
Total cost, maintenance and operation	45,695.31	0.511	49,336.96*	0.552*
Fixed charges (interest, taxes and insurance)	16,106.89	0.180	16,106.89	0.180*
Total cost	61,802.20	0.691	65,443.85*	0.732*
Power Consumption (kw-hr.)				
Passenger service (elec. locos.)	2,894,465		3,072,145	
Passenger service (M.U. Cars)	630,039		499,367	
Freight service	1,508,306		1,494,082	
Switching service	984,255		848,613	
Non-Revenue service	10,340		6,191	
Total used by electric locomotives and motor cars	6,027,405		5,920,398	
Signals	107,465		117,445	
Other company purposes	389,652		399,401	
Line loss	543,235		617,804	
Total used for company purposes	7,067,757		7,055,048	
New York, Westchester & Boston	676,144		636,058	
Other companies	1,205,699		1,255,139	
Total power used	8,949,600		8,946,245	
Maximum daily output	Tuesday, November 24th 343,300 kw-hr.		Friday, October 30th 316,630 kw-hr.	
Maximum swing	30,000 kw. Friday, Nov. 6—7.00 P.M.		29,800 kw. Sunday, Oct. 4—8.27 A.M.	
Maximum daily output	Tuesday, November 3rd 249,800 kw-hr.		Sunday, October 18th 256,155 kw-hr.	
Average daily output	301,902 kw-hr.		288,589 kw-hr.	
Power purchased from N. Y. C.				
Power purchased (kw-hr.)	1,244,021		1,306,017	
Cost of power	$16,097.67		$16,348.47	
Cost per kw-hr. (cents)	1.294		1,252	
Total Power:				
Total power consumed (kw-hr)	10,193,621		10,252,262	
Total cost of power (including fixed charges)	$77,890.87		$81,792.32*	
Cost per kw-hr. (cents) (charges)	0.764		0.789*	

*Revised.

TABLE XVIII. THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD COMPANY

STATISTICS OF ELECTRICAL OPERATION NEW YORK AND SHORE LINE DIVISIONS. MONTH OF NOVEMBER, 1914, COMPARED WITH MONTH OF OCTOBER, 1914.

Passenger Service.

	Express trains				Local trains				Multiple-unit trains			
	Eastbound		Westbound		Eastbound		Westbound		Eastbound		Westbound	
	November	October	November	October	November	October	November	October	November	October	November	October
Train-miles	49,436	50,385	53,768	54,032	29,128	32,941	23,839	28,622	21,569	19,338	22,552	19,363
Locomotive-miles	82,298	85,220	88,898	89,162	41,148	45,008	31,558	39,722	29,937	28,504	32,220	28,857
Car-miles	386,883	404,166	410,574	425,363	157,770	182,564	137,502	172,338	76,544	74,004	79,292	72,793
Ton-miles	23,880,554	24,483,292	24,654,186	25,697,939	7,314,489	8,444,023	6,432,307	7,812,994	5,093,352	4,755,814	5,296,525	4,634,919
Kw-hr. used	1,120,801	1,133,588	1,231,060	1,220,947	643,284	719,423	524,871	651,374	346,385	305,267	341,496	279,137
Locomotive-miles per train mile	1.66	1.69	1.65	1.65	1.41	1.37	1.32	1.39	1.39	1.47	1.43	1.49
Car-miles per train-mile	7.83	8.02	7.64	7.87	5.42	5.54	5.77	6.02	3.55	3.83	3.52	3.76
Kw-hr. per train-mile	22.67	22.50	22.90	22.60	22.09	21.34	22.02	22.76	16.06	15.79	15.14	14.42
Kw-hr. per locomotive-mile	13.62	13.30	13.85	13.70	15.63	15.98	16.63	16.40	10.71	11.57	10.60	9.67
Kw-hr. per car-mile	2.90	2.80	3.00	2.87	4.08	3.94	3.82	3.78	4.53	4.12	4.31	3.83
Kw-hr. per 1000-ton-mile	46.93	46.30	49.93	47.51	87.95	85.20	81.60	83.37	68.01	64.19	64.48	60.22

Operating Costs.

	Locomotive repairs		Power		Locomotive supplies		Engine house expenses		Enginemen		Trainmen		Total	
	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.
Trains hauled by locomotives:														
Cost per train-mile (cents)	17.15	13.80	19.33	19.89*	2.23	1.53	0.57	0.54	8.81	8.37	5.91	9.55	57.60	53.68*
Cost per locomotive-mile (cents.)	10.61	8.56	11.96	12.29*	1.39	0.95	0.38	0.34	5.41	5.20	5.88	5.91	35.63	33.25*
Cost per car-mile (cents)	2.45	1.93	2.76	2.79*	0.32	0.21	0.08	0.08	1.26	1.17	1.36	1.34	8.23	7.52*
Multiple-unit trains:														
Cost per train-mile (cents)	15.27	11.83	11.39	11.42*	0.24	0.16	0.91	0.78	5.17	5.20	8.84	7.53*	41.82	36.92*
Cost per motor-car mile (cents)	10.51	7.98	7.84	7.70*	0.17	0.11	0.62	0.53	3.56	3.51	6.08	5.08*	28.78	24.91*
Cost per car-mile (cents)	4.32	3.12	3.22	3.01*	0.07	0.04	0.25	0.21	1.46	1.37	2.52	1.98*	11.85	9.73*

*Revised

TABLE XIX. NEW YORK NEW HAVEN AND HARTFORD RAILROAD COMPANY.

STATISTICS OF ELECTRICAL OPERATION, NEW YORK AND SHORE LINE DIVISIONS. MONTH OF NOVEMBER, 1914, COMPARED WITH MONTH OF OCTOBER, 1914

Freight Service.

	Fast freight				Slow freight				Local freight			
	Eastbound		Westbound		Eastbound		Westbound		Eastbound		Westbound	
	November	October	November	October	November	October	November	October	November	October	November	October
Train miles	3,283	3,484	4,954	7,576	8,485	9,177	6.152	4.880	2,880	3.240	2.933	3,240
Locomotive miles	3,283	3,486	8,042	11,128	16,529	18,038	11,269	9,824	2,956	3,321	3.012	3,321
Loaded car miles	130,147	140,202	159,377	219,435	484,644	529,559	203,556	209,889	29,965	33,893	32,990	37,339
Empty car miles	335	203	60,545	106,040	57,346	59,801	184,978	177,831	16,304	16,339	12,072	20,456
Caboose miles	3,283	3,484	4,954	7,576	8,485	9,177	6,152	4,880	2,880	3,240	2,933	3,240
Ton miles	4,399,743	4,589,492	5,941,893	8,677,627	21,121,401	22,885,161	10,496,232	10,448,521	1,301,163	1,414,569	1,432,065	1,702,877
Kw-hr. used	108,749	112,033	186,401	265,088	566,983	571,972	340,830	294,602	118,423	110,757	106,650	114,828
Locomotive miles per train mile	1.00	1.00	1.62	1.47	1.95	1.97	1.83	2.01	1.03	1.03	1.03	1.03
Loaded car miles per train mile.	39.64	40.24	32.17	28.96	57.12	57.71	33.09	43.01	10.40	10.46	11.25	11.52
Empty car miles per train mile.	1.10	1.06	13.22	15.00	7.76	7.52	31.07	37.44	6.66	6.04	5.12	7.31
Ton miles per train mile	1,340,16	1,317,31	1,199.41	1,145.41	2,489.26	2,493.75	1,706.15	2,141.09	451.79	436.60	488.26	525.58
Ton miles per locomotive mile	1,340.16	1,316.55	738.86	779.80	1,277.84	1,268.72	931.43	1.063.57	440.18	426.55	475.45	512.76
Percentage of tonnage to rating	96%	95%	......	......	94%	93%	......	......	......	......	......	......
Ton-miles per hour	26,779	27,335	19,109	18,092	26,008	27,912	18,637	23,297	2,614	2,679	3,423	3,622
Average speed (m. p. h.)	19.98	20.75	15.93	15.79	10.45	11.19	10.92	10.88	5.79	6.14	7.01	6.89
Kw-hr. per train mile	33.12	32,16	37.63	34.99	66.82	62.32	55.40	60.37	41.12	34.18	36.36	35.44
Kw-hr. per locomotive mile	33.12	32.11	23.18	23.82	34.30	31.71	30.24	29.99	40.06	33.35	35.41	34.58
Kw-hr. per car mile	.81	.78	.83	.80	1.03	.96	.86	.75	2.41	2.07	2.22	1.88
Kw-hr. per 1000-ton miles	24.72	24.41	31.37	30.54	26.84	24.99	32.47	28.20	91.01	78.29	74.47	67.43

Ton-miles are based on weight of trailing load.
Percentage of tonnage to rating is found by dividing the total tonnage of trains as they leave Harlem River by the rating of locomotives hauling those trains.
Ton-miles per hour is found by dividing ton-miles by the total running time of trains between terminals.
Average speed is found by dividing train-miles by total running time of trains between terminals.

Operating Costs.

	Locomotive repairs		Power		Locomotive supplies		Engine house expenses		Enginemen		Trainmen		Total	
	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.
Cost per train mile (cents)	15.51	15.98	28.51	27.90*	0.54	0.63	0.48	0.58	10.66	10.44	17.83	17.46	73.53	72.99*
Cost per locomotive mile (cents)	9.69	10.19	17.82	17.79*	0.34	0.40	0.31	0.37	6.67	6.66	11.14	11.13	45.96	46.54*
Cost per 1,000-ton miles (cents)	9.95	10.16	18.30	11.73*	0.35	0.40	0.31	0.37	6.84	6.63	11.45	11.09	47.20	46.38*

*Revised

TABLE XX. THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD COMPANY.

STATISTICS OF ELECTRICAL OPERATION—NEW YORK AND SHORE LINE DIVISIONS. FOR THE MONTH OF NOVEMBER, 1914, COMPARED WITH THE MONTH OF OCTOBER, 1914

Line and Equipment failures.

	Line failures.																															
	Catenary insulator failures				Dead-end failures				Other-line failures				Equipment failures				Signal failures				Outside interference				Failures of employes				Total failures			
	Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.		Nov.		Oct.	
	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay	No.	Total delay
Between Woodlawn and Stamford...	1	22	1	14	..	..	..	..	1	..	1	8	..	..	1	143	..	..	1	..	2	..	3	..	..	..	..	..	4	22	7	165
Between Stamford and New Haven...	2	..	..	..	..	..	..	..	3	41	4	47	6	141	5	23	1	15	..	..	2	..	..	..	..	..	..	..	14	197	9	70
On New Canaan Branch..........	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
On Harlem River Branch..........	..	..	..	..	..	..	..	..	1	13	1	7	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1	13	1	7
In Yards..........	..	..	..	..	3	..	1	..	2	7	4	..	4	28	1	..	..	..	..	..	..	..	..	..	1	..	..	..	10	35	..	..
Total..........	3	22	1	14	3	..	1	..	7	61	10	62	10	169	7	166	1	15	1	..	4	..	3	..	1	..	..	..	29	267	23	242

Equipment failures

Class of service	Heated parts		Broken parts		Grounds		Miscellaneous		Total failures		Miles per failure		Minutes detention per failure	
	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.
Passenger....................	1	4	2	1*	20	25*	12	6	35	36*	7,071	7,328*	11	13*
Freight....................	1	2	1	2	3	2	0	1	5	7	13,183	9,506	56	60
Switch....................	0	0	0	0	0	0	0	0	0	0	40,964	39,624	0	0
Multiple....................	3	0	2	1*	2	0	11	11	18	12*	3,554	4,331**	18	7*
Total....................	5	6	5	4*	25	27*	23	18	58	55*	7,213	7,672*	17	18*

DISCUSSION ON "CONDITIONS AFFECTING THE SUCCESS OF MAIN LINE ELECTRIFICATION," (MURRAY), PHILADELPHIA, PA., JANUARY 20, 1915.

Alfred W. Gibbs: While recognizing the merit of the paper and its frankness throughout, I call attention to a few points where it is not sufficiently explicit, or with which I do not agree.

As for the first, I allude especially to the tendency of cities to require electrification through their limits, usually for the purpose of eliminating smoke. While it is true that the inhabitants of a small community may be as much inconvenienced as those of the largest city, it must be recognized that this demand, if fully carried out, means the establishment of as many steam locomotive terminals as there are separate lines of road leading into the city, the alternative to this being the electrification of the whole line. These local terminals would involve not only a heavy capital outlay, but a continued charge to expenses, due to the increased cost of the additional organizations and the less efficient use of the labor and equipment. This is properly a charge to electrification, and a heavy one.

Mr. Murray is not quite fair in his criticism of the engineers, who are responsible for the introduction of the direct-current system into the large terminals in New York City. It must be remembered that a long period of agitation had preceded the determination to electrify. The electrification was to avoid the objection to steam operation into the heart of a great city, and the first condition was that it should be a success from an operating standpoint. Is it surprising that the engineers in charge should turn to methods which had been thoroughly tried out? In at least one case the proposal to adopt the alternating-current system of transmission was not seriously advanced until after a very large outlay had been incurred for direct-current operation, a large part of which would have had to be absolutely thrown away to introduce the new system—and that untried on a large scale in this country. It must be remembered, further, that any serious operating failure would have jeopardized the whole investment and put back electrification for years. The engineers did not then have to settle the question of future extension of electrification. There was not then, and there may not be for a long time, any necessity to consider the question of future road electrification. By that time the air will have cleared considerably. It must be admitted that the operating results in New York have fully justified the engineers responsible.

I criticize, also, the statement that one pound of coal burned under the boiler of a central power plant will develop twice the drawbar power that the same amount of coal will produce when burned in a locomotive firebox. Proper allowance has not been made for the improvement in the modern steam locomotive with more liberal boiler capacity and with superheat. As an example, I have a record of coal per drawbar horse power for 27 tests of one locomotive on the locomotive testing plant at Altoona. It shows:

2.5 to 3 pounds	12 tests
3 to 3.5 pounds	7 tests
3.5 to 4 pounds	3 tests
4 to 4.5 pounds	1 test
4.5 to 5 pounds	4 tests

These are the rates when running, added to which are certain standby losses at terminals.

The figures for the coal per kilowatt-hour at Cos Cob, as given by Mr. Murray, when reduced to drawbar horse power for the locomotive, do not justify the statement of relative efficiency.

There is great difficulty in arriving at a fair basis of comparison between steam and electric operation. For road locomotives and through electric operation the problem is the simplest. For switching service, where the steam locomotive may waste more steam at the safety valve that it uses in the cylinders, the problem is very different. This part of the paper covers one of the greatest advantages of the electric operation.

In the table giving the cost of power the total costs are not given. Operation and maintenance account for 0.511 cent; fixed charges, including taxes and insurance, amount to 0.180 cent. No allowance is made for depreciation in the form of obsolescence in the power house and its equipment. From data of somewhat similar power houses, I should say that the fixed overhead charge, including depreciation, would be nearly double the figure given, say 0.35 or 0.4 cent., in the inverse ratio to the output. I regard this part of the expense account as a most important part of the accounting; otherwise, the time comes with startling suddenness when you have obsolete equipment, with insufficient reserve to replace it.

While making these criticisms, it is but fair to recognize the courage of those responsible for the electrifications described in this paper and preceding ones.

The paper is, in my judgment, very instructive, and all the more so because no claim is made for the 100 per cent perfection which we never realize.

George R. Henderson: Mr. Murray's paper on main line electrification will stand out as a "classic" giving, as it does, actual figures for cost operation on an alternating-current line. Several years ago Mr. W. J. Wilgus gave similar data for the direct-current lines of the New York Central. Both of these papers show that "uniformity" of traffic is just as important as "density" of traffic, otherwise the overhead charges of the power plant, which must be abnormally large, will more than "eat up," any saving due to fuel consumption, repairs, and labor, as the plant must take care of *peak loads*, and these can only be "smoothed out" when the traffic is uniform. As one hundred dollars per kilowatt will hardly cover power house and transmission lines, the importance of this observation will be obvious.

The fuel saving is stated as 50 per cent for a fixed drawbar pull, yet it must be borne in mind that this comparison is made with the old type of saturated steam locomotives, and modern steam engines, fitted with superheaters, will reduce this ratio very considerably, say to 65 per cent the amount of coal for such a locomotive as would be built today.

The fact that electric locomotives cost about three times as much as a steam locomotive of similar power must not be overlooked, also the flexibility of service of the latter is very important, as it may be transferred to any division desired owing to traffic conditions, and is not tied to a particular section whose limits are the lengths of the conductors leading from the power house. This is of prime importance to roads carrying intermittent business, such as live stock, which may have a week's work consolidated into a single night, or on the ore ranges in Michigan, which deliver cargoes to lake boats only during the period of navigation. Under such conditions the overhead charges would be out of all proportion to the work accomplished, and the electric locomotives would be idle a large part of the time, as they could be used only on electrified divisions.

However, we are glad to note that Mr. Murray does not wildly and enthusiastically proclaim electrification a " sure cure" for all evils, regardless of environment and operating conditions, as did some electrical experts a few years ago, and the conservatism for which he pleads will surely benefit the whole problem of electrification, by insuring the large expenditures chargeable to capital only where they will produce remunerative returns from operation.

E. H. McHenry: Mr. Murray strikes a very important keynote in the opening paragraphs of his interesting paper, in referring to the two-fold necessity for satisfying the requirements of both the public and the railroad as the touchstone of success.

The first requisite in the interest of the public may be fairly claimed as already satisfied, but the greater task of insuring adequate returns to the railroads upon the large capital investments required for conversion from steam to electric traction is as yet far removed from the state of an exact science. As stated by Mr. Murray, there are many places where electric traction could now be installed with profit, but the ability and ingenuity of the engineers will be taxed to the utmost degree in further widening and enlarging the present commercial field of application. The progress of recent years in the development of the art all tends in the right direction, as with experience and a clearer perception of the governing principles, the commercial efficiency of the invested capital grows greater, and there is no reason to doubt that the past progress will be continued in the future, with the result of greatly extending the present limits. With the growing tendency toward the consolidation of the best features of all the divergent systems into one system of greatest combined merit, the so-called war of the systems is already nearly at an end, and even now it will be found that there is more to be gained by a study of the possibilities afforded by the new method of train propulsion in securing the closest adaptation of its many points of merit to the operating requirements than by any probable difference between rival systems. There is room for much optimism in this general direction, although many cases will arise of special difficulty, in which the community or that part of the public most benefited by the improved facilities, are least able or least willing to pay the cost of the service, as in the case of communities using costly passenger terminals, and unless some satisfactory method can be devised for spreading the cost of such service over a city or a state substantially in the form of a tax, no practical solution of this difficult problem will be clearly apparent. In electrification, as in all other branches of engineering, the highest art will be shown by " the ability to make a dollar earn the most interest."

C. Renshaw: As a traveler climbing a mountain will often not realize the height he has attained until, pausing, he looks back over the route he has traversed, so, although from the beginning I have followed the New Haven electrification through its various stages, the summary which Mr. Murray gives of the electric mileage, equipment, and activity to which the road has now attained has impressed me particularly.

The application of electricity to the operation of every class of passenger, freight, and shifting service on an entire engine division of one of the busiest trunk line railroads of the country is an achievement that stands without a parallel in the entire world. It should be particularly gratifying, not only to those who are interested in electrical matters, but to the general public as well, that the undertaking is proving an economic as well as a technical success.

No less notable than the achievement itself has been the policy of the railway company in giving so freely to the engineering public the full results of its investigations and experience, not only with regard to its successes, but—what is of perhaps greater utility and certainly of greater rarity—with regard to its difficulties. The costs and other data which Mr. Murray has included in this paper form a valuable addition to the previous contributions which he has made.

As might be expected from experience with any original enterprise, Mr. Murray estimates that the electrical plant of the New Haven road, with the ten years' experience in construction and operation, now available, could be reproduced today for not more than 60 per cent of its original cost. It should be gratifying to all, however, that he also states the financial return will ultimately be sufficient to justify the actual expenditure to date, so that the courageous pioneer will not be a loser. Some road, he says, had to make the first break into the dark, but, from the data assembled, future results in the application of electricity in heavy trunk line territory can be predicated on assembled facts and not predicted from hypothetical analysis.

In considering the economies over steam operation, by means of which electrification can justify the investment which it requires, Mr. Murray puts the matter very simply by pointing out that these economies are normally of three kinds; *i.e.*, saving in fuel, saving in motive power maintenance and repairs, and saving in train-miles.

Broadly speaking, he says the costs of the first two items under electrification will be one-half the cost under steam operation. The saving in train-miles, however, depends very largely on local conditions and cannot well be generalized. Success in electrification, therefore, is primarily dependent upon density of traffic. This reduces the matter pretty well to its lowest terms and should help eliminate some of the mystery with which the savings to be effected by electrification have apparently heretofore been surrounded in the minds of many railroad operating officials.

A detail in the paper which deserves particular comment is the fact which is pointed out that an electric locomotive, like an over-willing horse, may work itself to destruction if permitted to do so. While it is perfectly possible to keep the cost of maintenance and repairs at one-half that of steam locomotives, under conditions most favorable to steam operation, Mr. Murray says it is only by the most rigorous and careful inspection and conformity to proper rules of operation that this can be done.

This fact is one of the most difficult to impress upon the minds of steam railroad operators, and it is to be hoped that the figures of 8.6 and 10.6 cents per mile for the maintenance and repairs of the general average of New Haven locomotives, as compared to the average of 3.96 cents per mile for the ten locomotives which have been properly overhauled, will have some effect in bringing about a more thorough realization of this important matter. Incidentally, this figure for the maintenance and repairs of ten locomotives, making 466,524 miles in the seventh year of their age, is a remarkable commentary on the reliability of such equipment when handled intelligently.

The paradoxical action of heavy freight trains in steadying the power house load instead of causing an increase in the peaks, as it was feared they would do, is also of interest. The fact that these trains, by dropping the voltage slightly, when drawing heavy accelerating currents, naturally cause other trains moving at high speed in the neighborhood to reduce automatically their power requirements, is readily appreciated when once noted, but is one of the many items brought out by actual experience which are often overlooked in advance calculations. Fortunately, in this case the unforeseen item is one which produces a favorable rather than an unfavorable effect on the operation of the system.

Many other items which Mr. Murray has set forth are also worthy of comment, and the entire paper forms a valuable contribution to the subject. We hope that it may serve as an inspiration to other engineers in active touch with the operation of similar properties to present their experiences with equal freedom for the general benefit of the art.

F. E. Wynne: Mr. Murray's paper is a very valuable contribution to the literature of electric railroading, not only on account of the operating data which it contains, but because of its clear exposition of the broad principles to be considered in deciding whether an electrification will be successful. In the past electrical engineers have been accused (and to some extent rightfully so) of advocating wholesale electrification of steam railroads without regard to the measure of success which might be expected. It is therefore very pleasing to find a representative electrical engineer taking the stand that an electrification is only justified when it is an assured success from the standpoint of all parties concerned.

The figure of $15,000,000 given as the expenditure for electrification of the New Haven Railroad to date indicates that the expenditure has been $120,000 per unit of motive power and $30,000 per mile of single track. Complete electrification of the New York-New Haven division will be accomplished without additional expenditure for trolley construction (which is a very large proportion of the total), and consequently these unit figures will be somewhat changed. The total expenditure per unit of motive power will gradually decrease and that per mile of single track will increase to some extent because of the large number of electric engines in service without increase in the mileage of the electric zone.

The further statement that the present plant could be reproduced at the present time with better operating results for not more than 60 per cent of the actual cost to date, indicates that for an installation similar to the New Haven the total cost may be made less than $70,000 per unit of motive power, while the cost per mile of single track will be in the neighborhood of $20,000. These figures, as noted by Mr. Murray, represent the cash outlay, and in determining the net cost of electrification they will be reduced by the credits for steam equipment replaced, etc.

The figures given for mileage show that passenger locomotives average approximately 170 miles each, daily, and that only 22 per cent of the total number of passenger trains have the full run of seventy-three miles. This daily mileage per locomotive is comparable to that secured from electric cars operating in rapid transit and heavy interurban service. It therefore seems reasonable to assume that when all through trains are electrically operated the average daily mileage per locomotive may be materially increased.

Similarly, the multiple-unit motor cars show an average of eighty-four miles each, daily. This is relatively low, but is undoubtedly due to the fact that local trains are bunched in the morning and evening rush hours to a greater extent than is ordinarily found. This low mileage, together with the fact that over half of the total multiple-unit trains operate with only one trailer per motor car, indicates that the railroad is not yet getting the full benefit of the rather large equipments on the motor cars.

The figures given in connection with the operation of the switching engines illustrate the remarkable reliability and operating economy of electric locomotives in this particular class of service. Such results lead us to believe that the field for the electrification of railroad yards is a large one and that considerable progress in this direction will follow a full appreciation of the success which may be expected. As density of traffic is one of the largest factors in determining the advisability of electrifying main lines, so the desirability of yard electrification will largely be determined by the degree of congestion existing. In such installations the initial expense may be reduced to a minimum where central station power is available.

Mr. Murray states that electrification very quickly increased the reliability of operation to some three or four times that of the steam operation it replaced. We do not altogether understand what is the measure of reliability used in making this comparison, but assume he means that the number of failures were from one-third to one-fourth as many as were encountered during steam operation for a similar period.

In connection with Mr. Murray's statement that maintenance and repairs on electric locomotives amount to approximately one-half those required for steam locomotives with equal weight on drivers, I should like to ask whether operation in equal service also should not be part of the basis of comparison.

The remarks regarding the differences in the natures of electric and steam engines are particularly pertinent, and Mr. Murray's plea for electrically-trained men in the administrative department of electrified steam railroads points out one of the things which is of the highest importance in securing the fullest measure of success in electrifications.

It is interesting to note the results secured in connection with energy consumption, as these closely check the accuracy of calculations made in connection with this service, thus illustrating the fact that the energy consumption with electric operation can be very closely predetermined where trains are operated on a steam railroad basis; that is, with definite schedules and definite stops. The figures given show, further, how rapidly the consumption of energy increases with the increasing number of stops as indicated by the several classes of service. Since the electrical equipment is merely apparatus for converting electrical into mechanical energy, it follows that with increased unit energy consumption increased work is required of the electrical equipment, and therefore electric locomotives will safely handle much greater tonnages in through service than in local service. They will also handle greater tonnages at moderate speeds than can be operated at high speeds.

The information regarding the improvement of load factor and smoothing out of the curve of power station output with the addition of trains (even though those trains were comparatively heavy) illustrates a principle which has been found to exist in connection with city and interurban electric railways, namely, that the peak load on the system increases less rapidly than in proportion to the increase in number of cars or trains operated. However, in city and interurban systems this is probably due more to the fact that, as the number of cars operated increases, a smaller proportion of the total are starting simultaneously, rather than to the flywheel effect of the moving cars. We are inclined to the opinion that with further increase in the number of trains electrically operated by the New Haven Railroad some benefit in the improvement of load factor and reduction of peaks will be secured from this source, as well as from the flywheel effect of the moving trains.

The reduction in cost of the trolley construction which has been made since the initial installation shows great progress in the right direction. However, we believe that it is not yet sufficiently low to represent maximum all-round economy. This belief is strengthened somewhat by Mr. Murray's statement of the extraordinary reliability of the overhead construction in stormy weather. This great degree of reliability leads us to question whether part of the cost of the overhead construction may not be due to its being designed with an unnecessarily great factor of safety.

In connection with Table XVII, only interest, taxes, and insurance are specified as fixed charges. I should like to ask whether a depreciation allowance is included in the figures given.

I feel that the Institute is to be congratulated upon securing the presentation of such an able paper, and trust that its author may continue to make public his valuable data regarding the principles of railroad electrification, to the end that electric operation of steam railroads may be extended and may be attended by the greatest success.

Philip Torchio: The growth of large electrical undertakings has been the evolution from small beginnings. In the case of railroad electrification, however, the problem has been quite different. With an established heavy traffic which does not allow of interruption or delays, a new system of traction is to be substituted, requiring radical structural changes all along the line and an entire new system of power generation and distribution.

The engineers confronted with the problem have attacked it in a comprehensive and thorough manner, developing complete systems as self-sustaining and autonomous as the progress of the art allowed them to accomplish at the time. Mr. Murray has described the operation of a system which really went a step further and anticipated the progress of the art by many years. The importance of this epoch-making " experiment " is naturally very great.

The author emphasizes the point that the experience of the New Haven will benefit the other railroads in solving their problems of electrification. In this connection I wish to call attention to the item of investments in power houses and power-transmitting lines, which in all the original electrifications were assumed as a necessary part of the equipment, but which in late years the railroads have found more economical to omit from their investment, substituting purchased power delivered to them by central-station power companies. The New Haven has purchased from the New York Edison Company all the power required for its western section of the alternating-current lines and terminals. The Pennsylvania Railroad has purchased from the Philadelphia Electric Company the power for the electrification of its main line from Philadelphia to Paoli and for its other contemplated extensions around Philadelphia. The London, Brighton and South Coast Railway Company buys current from the London Electric Supply Corporation, Ltd. The Chicago, Milwaukee and St. Paul Railway and the Butte, Anaconda and Pacific Railway buy power from the Montana Power Company.

Along every large railroad where the heavy traffic would warrant electrification there is, or can be made readily available, abundant supply of electrical power from power companies. These companies, by averaging the power demand from a great diversity of users, reap economical advantages in investment and in generation and distribution of power which the railroad cannot secure under independent generation. I wish to call attention to this phase of the problem, as the saving in investment in stations, substations and transmission lines may represent a sensible item in the investment of railroad electrification.

The central stations, besides offering investment and operating advantages, can furnish, in addition, a more reliable supply of power, because they command the best knowledge of the art of electricity supply, which is their exclusive and specialized business.

W. A. Del Mar: This paper is interesting not only as a statement of operating results with the single-phase system of traction but also as a basis of comparison between steam and electric traction. Indeed, so nearly equal are the principal electric systems from an economic point of view that we may well afford to neglect their rivalry in view of the more vital rivalry between steam and electricity. I believe that the " battle of the systems " was largely caused by the advocates of each system being so carried away by enthusiasm as to be unable to tell the whole truth, whether in defending their own or criticising the others. Here, at last, we have a presentation of operating results, making it unnecessary to base conclusions upon specious arguments about details.

It is unfortunate that the operating costs are given for only two months of the year. The results would have been more valuable if they had been based upon a complete year, as it is almost impossible to select two really representative months, especially in view of inevitable variations of maintenance costs of equipment. The omission of the annual fixed charges is also to be regretted, as it is well known that the running charges can be made less with electric than with steam traction, but it is not always clear whether the fixed charges added by the electrical plant will destroy the favorable balance due to operating economies. Various cost data are presented, but in such form as not to be available for calculating fixed charges. We do not know, for example, whether the $15,000,000 expenditure mentioned by Mr. Murray includes the cost of reducing telephone disturbances and of altering the right-of-way to conform with electrical requirements.

One cannot help being appalled at development charges amounting to 40 per cent of the entire investment, as one would infer from Mr. Murray's statement that the present system could be replaced for 60 per cent of the original investment. An interesting feature about the installation has been the development from the complex to the simple in mechanical details, and *vice versa* in the electrical features.

Examining the operating costs with the view of comparing them with steam operating results, one is confronted by a series of questions which, if unanswered, will render such comparison difficult. Having gone to great trouble to segregate and clearly present the operating costs, Mr. Murray proceeds to obtain unit costs by dividing these operating costs by car mileages and train mileages of unspecified nature. It is to be hoped that Mr. Murray will state the nature of the mileages with greater detail, particularly as to whether they include yard switching and light locomotives. These two items may easily amount to 15 per cent of the entire mileage.

The fixed charges given for the Cos Cob power station appear to be very low. It would be interesting to know whether they include depreciation.

An interesting feature of the New Haven installation is the use of meters on the locomotives. This enables an intelligent estimate to be made of the relative cost of different classes of service, such as passenger locomotive, freight, and multiple-unit. Meters on locomotives are not very accurate, due to vibration, but it is interesting to note that, provided the vibration is impartial with respect to making the meters read high or low, the probable error in the aggregate reading will be quite small, due to the large number of locomotives. Thus where there are

100 locomotives a possible error of 20 per cent in each meter will cause a probable error of only $\frac{20}{\sqrt{100}} = 2$ per cent in the total.

Electric railway men should feel very grateful to Mr. Murray for this paper, which will long be consulted as a classic upon a great engineering topic.

R. H. Wheeler: In this paper there comes a boon to those interested in the application of electricity to train movements, in the practical definitions of conditions which affect the success of a railroad electrification, supplemented by copious data resulting from an extended period of operation. The haze from the " shots " of the " battle of systems " now clears away from the single-phase side of the field, showing an interesting array of results achieved.

Two points, from the many ably put forth, appeal to me for special emphasis. These are vital to the success and quantity of success, which latter is the chief " lure " of electrification.

First.—The careful analysis and choice of a form of electric power which may be standardized for all classes of train service on that road.

Second.—The " inheritance " to electric operation of " steam-trained " operators.

Under electric operation the power plant is separated from the locomotive, and it is evident that the economy of energy transmission, from its source to the wheels of the engine, is paramount. The overhead contact wire lends itself very readily to this transmisson duty, in yards, terminals, on the road, and elsewhere. For reasons of high economy of transmission and diversity of transformations, Mr. Murray suggests that this wire be energized with 11,000 volts single-phase, 25-cycle power. By the use of the mercury-arc rectifier the admirable qualities of the series direct-current motor can be retained. This motor is especially desirable where the " density of traffic " factor is highest, as in suburban and terminal electrification, on account of its accelerating capabilities and weight economies, both in itself and its control. However, to carry about a rectifier upon the class of equipment employed in terminal service, even if rectified single-phase current were suitable, would impose a serious handicap in both weight and control complication. Rectified single-phase current is not ideal for direct-current motors of the usual design, requiring increased thermal capacity and thus weight. These reasons militate against the " standard " proposed as suitable for all classes of train service.

However, by placing the rectifier in the roadside substations and taking advantage of the economies and freedom of disturbance to other local circuits of a balanced three-phase, 60-cycle supply, another " standard " results which supplies, over the overhead contact wire, power at 3000 volts direct current, and which has the desired essentials of transmission economy and standardization of motive power equipment. In the case of heavy grade divisions operated by rectifier substations, engines arranged for regeneration would be employed. This second " standard " is offered to emphasize Mr. Murray's definition of the successes arising from a choice of energy which can be standardized. A railroad which, in its initial electrification, utilizes a system which is capable of being extended through successive increases of electrically-operated territory has gone far to insure successful electrification.

With the figures Mr. Murray presents, indicative of the successful operation of the New Haven motor cars and a-c.-d-c. engines since the last overhaul in a well-appointed maintenance shop, it is evident that the straight alternating-current engines will show greater economies. When the data are available from the Butte, Anaconda and Pacific Railroad, Chicago, Milwaukee and St. Paul Railroad, and Canadian Northern Railway, giving results of operation, especially as the latter is to employ 2400-volt motor cars, another decisive step towards standardization can be made.

Secondly, I wish to emphasize the important part that " heredity " plays. Mr. Murray states that a thorough understanding must be had of the fundamental differences between steam and electric operation. Electric operation is a more exact science than steam operation, since a great many of the variable factors are removed. Chief of these, the power generating plant, is removed from the hands of the fireman, and he cannot now produce more power to get an overloaded engine over the road. Certain rules and axioms the officials of the operating department must appreciate in adapting themselves to the era of electrification.

As well, the proper care and thorough inspection of electric equipment should be insisted upon and the long life resulting from renewals and not repairs be gained. It takes thorough investigation and time to care for such equipment, and in the early stages a little more leeway should be given the shopmen. Cooperation in these things will produce the economies which make an electrification successful.

W. S. Murray: The writer takes this opportunity of expressing his appreciation of the many interesting points and suggestions that have been brought out in the discussion of the paper.

Before specifically commenting on the individual discussions, the writer desires to draw attention to an (apparent) error in the paper, which appears in Table XVII, under the statement covering the output of the Cos Cob station. In that statement the fixed charges are named as 1.8 mills per kw-hr. This statement is based upon certain discounts allowed by the railroad company on installation charges, and also does not include depreciation. For outside comparative purposes, however, the rate of 1.8 mills should be changed to 2.9 mills, the latter figure being based upon an eleven per cent rate on the total investment involved, carrying with it interest, insurance, depreciation, and taxes. The total cost, therefore, for current would become 8.01 mills per kw-hr. instead of the rate named in the paper of 6.91 mills, the former and larger figure being then in form, as previously stated, for comparative purposes.

I am indebted to Mr. H. P. Davis, vice-president of the Westinghouse Electric and Manufacturing Company, for his valuable discussion, and it is hardly necessary for me to point to the fact that not a little of the success in the application of high-tension alternating current to heavy traction systems is due to Mr. Davis. In particular we are indebted to Mr. Davis for the system of control that is used for electrical sectionalization, and, while the New Haven system now in service has been modified considerably to conform to the rearrangement of its circuits to reduce to a minimum electromagnetic induction, the earlier and basic elements which were worked out largely under the suggestion and cooperation of Mr. Davis are found in the system now controlling our entire lines.

Mr. Davis's long connection with the development of heavy electric railway equipment lends authority to his voice in commenting on the proper treatment which should be accorded electrical equipment. It might be said of electrical as compared with steam equipment, that *it is possible to get twice as much out of it and it is four times as different*, and the brains and fingers that are to handle the electrical equipment should have an electrical rather than steam instinct governing them, for the rapid progress and success of the application of electricity to heavy traction railways will largely depend upon the recognition of these simple facts.

Of the various departments of a railroad, covering respectively executive, traffic, transportation, legal, operating, and engineering matters, it were natural and seemingly logical to assign an electrification problem to its engineering department, and yet the advance of the art in the application of electricity for heavy traction purposes has been so rapid that I venture the opinion that ninety per cent of the chief engineers of all the roads in this country, being so perfectly unacquainted with the underlying principles of the generation and application of electricity, would shrink from such a responsibility. It is to be noted that a few roads have placed their engineering department under the jurisdiction of their operating department, under which arrangement an assignment of the problem to the engineering department jeopardizes still further the desired result. The railway company will do well, therefore, when it decides to make so radical a change in its motive power, involving millions of dollars, to assign that responsibility solely to a man qualified to assume it, and also to see to it that his hands are not tied by having to report to officers in the engineering and operating departments, who are unacquainted with the governing principles of electricity; indeed, on the contrary, it is my opinion that these departments should be requested by the president to cooperate to the full with the officer responsible for the work, thus clothing rather than robbing him of the authority so essentially necessary in producing an *electrical* plant to accomplish an *electrical* result.

As the above is true in the matter of electrical engineering and construction, it is to a very great extent true in the matter of operation, and, as pointed out in the paper, while no radical change is necessary in the general railroad organization of today, I cannot too greatly emphasize the absolute truth that when a railroad company has adopted electricity to be its motive power the operating officials should state the *schedules* and *consist* of trains, and then abide by the decision of the electrical officer (whose duties might be defined as " in charge of electrical engineering and construction and the features of electrical operation ") as to what power, both generative and motive, is necessary.

In the past there has been an appalling attitude on the part of officials of some steam railroads electrifying—rather than welcoming the selection of electrically-trained men for positions such as superintendents of electrical shops, road foremen of electric engines, master mechanics for electric engines, to insist that these positions be filled by men who have occupied seemingly analogous positions under steam locomotive conditions, notwithstanding their past environment, experience, and adaptability to the new and different conditions confronting them make them unfit, both from a safety and economic standpoint, to serve. Railway managements are now waking up to these facts, and in the last year great improvement in the electrical *personnel* of the operating departments has resulted. There is much along these lines to be accomplished yet, and dire necessity, as much as anything, has brought about the real and final awakening to a differentiation between electrical talents that apply and those of steam that do not. This information is too vital, and, indeed, as it constitutes the very rivets and gusset plates of the electrification bridge over which we are crossing to more economic, safe, and satisfactory railroading, it has a fitting place here. It has been a strenuous past; the bills have all been paid, and as sure as they represent the millions of dollars lost in the past, so do they equally represent the millions of dollars to be saved in the future, and so at least we can say it has taught us " how not to do it."

Referring to Mr. McHenry's comments: It has always seemed to me that electrification has been an advantage to " the many" at the expense of " the few." While it is true that electrification for *economy's* sake bids fair to preëmpt the use of it for *necessity's* sake, still it is fair to believe that the consideration of electrification of city terminals carries for the present a more popular justification, and if it can be proved beyond doubt that the electrification of city terminals imposes a financial burden upon the railroad, it would seem to me that Mr. McHenry's suggestions of an " outside " tax should find justification.

In Mr. George R. Henderson's valuable contribution to the paper an excellent point is made with regard to the uniformity of traffic being a most important adjunct in securing the economies of electrification. In nearly all the situations of electric power generation and distribution we seldom, if ever, hear of one wherein a 100 per cent load factor obtains. There are thus certain hours in a day, and in railroad work generally two such periods (if only the passenger service is operated by electricity), when the power requirements are at a maximum. It is thus seen that at all other times of the day and night full advantage is not being taken of the total electrical investment. Realization upon Mr. Henderson's suggestion is to a large measure accomplished by the electrical movement of freight as well as passengers, as the maximum power demand for the former can be made to follow at the time of minimum demand for the latter. Those who have studied the matter of load factors in their application to lighting and street railway properties have accustomed themselves to such figures as from 35 to 45 per cent and sometimes reaching 50 per cent load factor. I have no doubt it will be of interest to state that in plotting the combined load curves of the New Haven passenger, freight, and switching services without any rearrangment of the schedules as they are made up today a load factor of 75 per cent is secured, which figure, I am sure Mr. Henderson will agree, bespeaks the uniformity of the density of traffic at least in the New Haven case. It is apparent, therefore, that in the study of electrification equal consideration should be given to both freight and passenger movement.

With regard to fuel saving, if the economy of generating units remained fixed, it would be fair to grant Mr. Henderson's point with regard to the change of ratio from 50 per cent to 65 per cent. On the other hand, the thermal efficiency of generating plants is easily keeping pace with that of steam locomotives, and, granting this, there are no other constants or variables which will tend to alter the ratio of one to two in favor of the fuel economy of drawbar pull by central electrical stations *versus* steam locomotives.

Mr. Henderson's point with regard to the transfer of steam locomotive power to different divisions of a road where congestion may require is interesting; I can conceive, however, of a division electrifying, with economy, not inclusive of the financial credits due to the steam locomotives replaced, thus automatically providing steam locomotives for service in the congested districts. The principal value of Mr. Henderson's observation on this matter, to me, is in pointing out that every electrification is a study in itself, and in electrifying one division its effect may be felt in many different ways in other divisions.

I am indebted to Mr. F. E. Wynne for his unit analysis of investment cost. I think that he has transformed electrification investment into a very unique and interesting basis for consideration. His assumption with regard to the limitation of passenger locomotive and multiple-unit car mileages is entirely correct; the morning and afternoon suburban traffic to and from New York City, with its close headway, makes the problem of securing high car and locomotive mileage most difficult.

Answering Mr. Wynne's question as to the statement of increased reliability of operating when electric was substituted for steam service, I would advise that this was, as he surmised, upon a failure basis. A fair average for steam locomotive operation might be cited as 5000 miles per engine failure, whereas with electrical operation it certainly should be 12,000 and in a number of instances on the New Haven it has been as high as 18,000, and it is my understanding that both the Pennsylvania and the New York Central have reached figures higher than this, our own mileage having been lower than the others, due chiefly, I think, to the requirement of the dual a-c-d-c. operation.

I am entirely in agreement with Mr. Wynne that the maintenance and repairs on electric locomotives should be compared to those of steam upon the basis of equal service and weight on drivers.

Again I find comfort in Mr. Wynne's emphasis upon the high importance of securing the proper electrical administrative forces in the electrified zones of steam railroads.

Answering Mr. Wynne's inquiry with regard to Table XVII, as explained in my general note at the beginning of this discussion, no allowance was made for depreciation under fixed charges.

Mr. Philip Torchio's contribution is of great interest, and shows the trend and possibilities of large central-station power in the field of electrification. The introduction of an alien power to produce drawbar pull upon a railroad is certainly a departure from past practise. The acceptance of this practise hyphenates the name of the mechanical superintendent, and the central power stations who have relieved him of a part of his duties will do well to see that this new step is justified, and it can only be justified by a practically perfect continuity of service.

Many railroads electrifying will insist upon the internal control of their entire power, others will mingle purchased power with their own power, and, finally, still others will depend entirely upon purchased power. I see no particular difficulty arising in any one of these three arrangements of supply, and I have agreed with Mr. Torchio that the only true basis for a contract by a railroad for the supply of outside power will be that that power can be supplied with the same reliability as the power could be produced by the railroad company and at equal cost.

The higher thermal efficiency secured in the use of large generating units affords an opportunity for large central-station plants to sell power to railroads, a measure of the justifiable profit in this sale being in the difference in efficiency between the smaller generating station (required by the railroad) and that of the central station. Such an arrangement as Mr. Torchio has pointed out provides an economical supply of power, and at the same time obviates the necessity of the railroad company investing in this feature required for electrification. Indeed, and digressing for a moment, I will go a step further under Mr. Torchio's thought and say that in these days when railroads are so hard up for cash the " equipment trust " offers a relief in the matter of the purchase of electric motive-power equipment, leaving as the only cash investment necessary, on the part of the road electrifying, that incident to the cost of the distribution and contact system required for the operation of its trains, and such buildings or modifications of buildings as will cover the shopping requirements of the new electrical equipment.

Commenting on Mr. Alfred W. Gibbs's valuable contribution in the discussion: His first point is well taken, and has been long recognized as one of the serious capital and operating expenditures where the problem of electrification is applied to deviating lines entering a city, and unless, as Mr. Gibbs points out, each one of these lines is electrified throughout the entire division, it is necessary to arrange local terminals to permit a change from steam to electrical operation. Such a condition, for example, is manifest in the study of the electrification of the various lines of the New York, New Haven and Hartford, the Boston and Albany, and the Boston and Maine Railroads entering the city of Boston. As Mr. Gibbs advises, this is quite properly a charge to electrification, and a heavy one. On the other hand, large cities gridironed with their entering roads may have a density upon these tracks which will permit the terminal charges and still be within the economic limit of electrification. The tendency will be, of course, to electrify roads entering the cities upon which the greatest traffic obtains, and those having a lesser density will in turn be electrified as increased density justifies. The difficult financial situations in which the railroads of today find themselves are becoming better appreciated daily by the public, and it is safe to assume that, as density of traffic is the controlling factor in electrification, a city's people will see the justice of such a proposed procedure.

I fear my little remark with regard to the third rail having "gone to seed" has unwittingly lodged in Mr. Gibbs's vermiform appendix, and will necessitate a slight operation on my part. Let me hasten to disclaim any seeming attitude of criticism on my part with regard to the engineers who were responsible for the introduction of the direct-current system, particularly in the New York City terminals. That the Pennsylvania Railroad Company has adopted the overhead system for its Philadelphia electrification, I confess, offered partial grounds for the suggestion that the third rail was past its flowering stage.

Mr. Gibbs's table showing the economy of steam locomotives with more liberal boiler capacity and with superheat is most interesting. The note that Mr. Gibbs adds, however, that "*these are the rates when running, added to which are certain standby losses at terminals,*" transforms "test" into practical conditions, and, as explained in my commentaries on Mr. Henderson's discussion, the improvement in thermal efficiency of central power stations can easily keep pace with any similar improvements in the steam locomotives. I feel sure that Mr. Gibbs will later find that my statement with regard to this matter is correct, and, if he does so, will take the first opportunity to withdraw his criticisms of my statement that "one pound of coal burned under the boiler of a central power plant will develop twice the drawbar power that the same amount of coal will produce when burned in a locomotive firebox." When I made the statement I had, of course, reference to the average conditions of practical operation.

As explained in the paragraph preceding my commentary on the general discussion, the figures for depreciation upon the Cos Cob power station were not included, and for comparative purposes they should have been allowed. Mr. Gibbs has named a rate of 0.35 or 0.4 cent per kw-hr., as the amount that should apply, and it is to be noted that upon the basis of 11 per cent upon the total investment made, covering interest, insurance, depreciation and taxes, the figure 0.29 cent, while less, does not differ greatly from that suggested by Mr. Gibbs.

Mr. Wheeler discusses most interestingly two vitally important points in the matter of electrification:

(1) The form of electric power which may be standardized for all classes of train service.
(2) The inheritance in the electric zone of "steam-trained" operators.

With regard to (1), the question of the location of the rectifier on or off the locomotive will always admit of local analysis for the most economic result. Mr. Wheeler has pointed out some very interesting possibilities in this direction.

With regard to (2), the matter of electrical administration, I have already expressed myself at such length on this matter that it will be only necessary to acknowledge with interest Mr. Wheeler's concordant sentiments.

Mr. W. A. Del Mar has asked some very pertinent and interesting questions, which I am very glad to answer. With regard to the expenditures made to reduce telephone disturbances, and of altering the right of way to conform with electrical requirements, these were included in the general figure of $15,000,000 mentioned in the paper. It is of interest, however, to note that past experience has indicated a proper method of laying out the transmission and distribution system whereby automatic compensation for telegraph and telephone disturbance can be secured for a very nominal amount. For example, in the case of the electrification of the four-track lines between Stamford and New Haven, the arrangement of transmission and distribution for the most economic traction result proves the most efficacious for reduction of the telegraph and telephone disturbances.

It is of interest to note that Mr. Del Mar is appalled at the development charges of the single-phase system, and, while I am at a loss to understand how a " fact " can be presented in an " ingenious way," as an example of a reduction of costs, our strain insulators in 1907, when we first began the electrification, cost $63. Today, with factors of safety three times both the electrical and mechanical values they had in their original installation, the cost has been reduced to $7. A longer experience in the handling of work-train service and the administration of construction work upon those work trains are points along the curve representing 40 per cent in the reduction of construction, etc.

With regard to the four questions Mr. Del Mar has asked, I am glad to answer them as follows:

(1) Q. Do these mileages include or exclude yard switching?

A. The mileages given for both passenger and freight service do not include yard switching (*yard switching* is taken care of by yard switchers designed especially for that purpose).

I would advise, however, that the locomotive-miles as shown on line 2 of the operating statistics, in the case of both the passenger and freight service, include the mileage of locomotives in trains and also the miles " run light " between engine-houses and stations. In figuring the passenger operating costs, however, the mileage of engines " run light " between stations is also included, thus giving the total passenger locomotive-miles, and in figuring the operating costs on freight locomotives likewise the miles of light moves and the mileage of locomotives switching at way stations on the main line are also included. It would doubtless be of interest to Mr. Del Mar to know that we have added a third sheet of statistical information having reference only to yard switching mileage and yard switching costs, which sheet had not been inaugurated at the time the paper was written.

(2) Q. If they exclude yard switching, do not the operating costs appear unduly high? If they include yard switching, how is it estimated?

A. The above answer to Question 1 doubtless serves as an answer to Mr. Del Mar's second question. While agreeing with his statement that the costs are high, I only hope that I have made the reason for this clear, especially in view of the typical record of the costs of maintaining the ten engines which at the time of the paper had received a full overhaul in the new shops. As previously explained, some of these engines had run 300,000 miles without undergoing any general repairs.

(3) Q. Are light locomotive mileages included in train-miles?

A. The train-miles did not include the mileage of locomotives "run light," but have been recorded and are included in the total locomotive mileage in computing the unit cost per locomotive-mile both in freight and passenger service.

(4) Q. The fixed charges given for Cos Cob power station appear to be very low. It would be interesting to know whether they include depreciation.

A. As explained in the previous part of this discussion, they did not include depreciation.

Mr. Del Mar's point with regard to the negligible error of meter registration on locomotives is very interesting, and so far as we have been able to determine, the meters have been an accurate and valuable adjunct in the determination of the general distribution of power.

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THE BEST CONTROL OF PUBLIC UTILITIES

BY FRANK G. BAUM

ABSTRACT OF PAPER

The author states as an axiom that "the best control of a public utility is that which develops an eagerness and ability on the part of the company to furnish the service, and an equal eagerness and ability on the part of the consumer to purchase the service." Five elements requisite for the development of this eagerness and ability on the part of the company and the consumers are stated and analyzed.

One of the important elements is confidence in the company and its rates, and the author states his conviction that class rates are absolutely necessary for the best development of the business. All classes of consumers benefit by a diversified use of electric energy, which makes lower rates possible. The principle at the bottom of all rates is to make the plant earn all it can during every hour of the day so that the burden of the investment may be distributed. The same principle applies to nearly all public utilities, railroad, telegraph, express and postal service.

There is confusion in the minds of consumers because rates for power are lower than rates for electric lighting, and the electric energy for the two very different kinds of service is measured in the same units, kilowatt-hours. But in the similar case of railway service, there is no feeling that passengers should be carried as cheaply as freight, because it is realized that the two kinds of service are very different, and one is measured in passenger-miles and the other in ton-miles. Therefore the author urges the establishment of class rates for electric service as being more scientific than the methods in general use at present, and less likely to lead to misunderstanding. Examples are given to show that the lighting consumer's rate must be much higher than the power consumer's, because the investment and cost of operation to serve the former are greater than are required to serve the latter, and because, for the same peak demand, the total energy used by the power consumers is much greater than that used by the lighting consumers. The paper outlines the method for determining class rates for different classes of service.

IT MUST be evident to anyone who has given serious consideration to the subject of the control of public utilities that it is necessary always to have in mind the following as an axiom:

The best control of a utility is that which develops an eagerness and ability on the part of the company to furnish the service, and an *equal* eagerness and ability on the part of the consumer to purchase the service.

Note that there must be both eagerness and ability on each side in order to promote the best interests of the business. Now how are we to determine the best way in which to develop this eagerness and ability on the part of the company and the consumer?

1. There must be developed a diversified use of electric energy.

2. Fair public service commissions must act as boards of arbitration between the company and the consumer.

3. The rate of return on the investment must be liberal.

4a. There must be confidence in the company and its rates, and *class rates* are absolutely necessary for the development of the business; 4b. Uniform class rates for a system or territory are advisable when rates are fixed by one commission.

5. There must be some incentive for the company to make economies in construction and operation.

It will be profitable to review these five requisites in some detail and try to make clear some of the points now causing confusion in the minds of some consumers and investors.

(1) It is necessary for the company to know the possibilities of the use of electricity in its territory and incessantly encourage the use of this form of power throughout its territory. It need hardly be explained that the fundamental characteristic of electricity as an aid to human endeavor is that it can be produced at certain central points and distributed by means of electric wires throughout a tremendous area. It is thus carried to every place where power or light is needed, the original power being divisible into an infinite number of parts, each part performing its function at its proper place in a perfectly predetermined and efficient manner. Also it must be understood that electricity cannot be stored in large quantities, but must be produced the instant it is used.

It is also well to bear in mind that most labor or effort can be stated in terms of energy, and when power can be applied to displace physical energy there is almost always a very large gain in efficiency and especially in output. And always when the larger efforts required are done by power instead of by human labor, the result is a stimulation of other industries. For example, when a railroad takes the place of teams for hauling between certain points, the cheaper method of hauling becomes a primary cause for the establishment of other industries which were not practical before the advent of the railroad. Similarly, cheap power in a district is generally a primary cause for the establishment of other industries not possible before the advent of cheap power. The result is that railroads and electric power lines, which, like steamship lines, are primary causes of the establishment of other industries and tend to promote general prosperity, should be encouraged, if not subsidized. Illustrations of the advantages to all consumers of a diversified business will be given under (4).

(2) In the determination of what is the best policy for a public service company, the question of the proper rates for different kinds of service is often a matter of contention between the company and the consumer, and as the service which a railroad or a power company furnishes is a natural monopoly, and competition does not promote the eagerness desired on the part of the consumer or of the company to purchase or furnish the service, the regulation of the rates is now generally delegated to public service commissions, which are really boards of arbitration to determine what is for the best interests of the business, considering both the company and the consumer.

(3) In the determination of reasonable rates for service the commissions, in addition to the ordinary operation and maintenance expenses, take account of the capital invested, and capitalize the loss in interest covering the unproductive period during which the business was being established, and allow generally some capitalization of the going value of the business, the latter often being made up of a number of elements, some of which are difficult to determine with great exactness. The result is that rates are usually allowed liberally so as to leave no doubt of the above items, and quite generally when this is done there is no resort to the courts. The rate of return must, of course, depend on the risk, the character of the country, the stability of the business, and the economy of the manufacture of the power facilities.

While a rate of return is generally allowed for the initial period of a company's business, no extra return from business originating on new extensions is generally allowed. The reluctance of companies to make extensions into new territory is largely due to this fact. As a matter of fact, all extensions into new territory should be treated as unprofitable for such period as is necessary for them to become paying, and a capitalization of the losses should be allowed the same as in the establishment of a new enterprise.

The amount of time necessary for a business to become remunerative may vary from one to ten years, and generally if one can start and produce a paying enterprise in five years it may be considered a success. If the earnings commence at zero and become remunerative at the end of six years, the loss in interest amounts to about 18 per cent of the investment. All unremunerative extensions should be treated in the same way, with the result that from 10 to 20 per cent capitalization should be allowed on the total investment in order to promote extensions by the established companies. Otherwise the result will be, if no allowance is made for extensions, that the established companies will not make extensions into new territory, but these will be undertaken instead by new companies which will be allowed to capitalize the loss in interest at a higher rate than the established companies. Extensions into new districts are extremely important, because we must not only consider those who enjoy the service, but those who would like to make use of the same service.

As an example, I have a ranch located 35 miles from the nearest railroad point. The Southern Pacific Company surveyed a line five years ago, but owing to general conditions has never built the line. Now, a reduction of freight or passenger rates to the valley farmers is no help to me; in fact the reduction to the valley farmers may be one of the reasons I do not get railroad service. Moreover, I am not much concerned whether or not the rates to be charged me during the first ten years are 20 per cent higher than they will be later. What I want is railroad service and I am willing to pay high rates and a bonus to get it. The district has as much available land as the Imperial Valley and can support a railroad, but I and the other farmers do not get the railroad service because there is no incentive for the railroad to go into new territory.

All the early companies risked large sums in the early stages of the electrical business and this should not be lost sight of in fixing rates at the present time. A certain manufacturing company at one time had a possible loss of about $10,000,000 facing it before it made its type of steam turbine a success. The price at which turbines are sold must, of course, absorb this amount, but the gain in efficiency obtainable, of which the public gets the benefit, makes the $10,000,000 insignificant. If the manufacturers are entitled to something for their risk, is not the electricity supply company that installed reciprocating engines to be replaced by turbines entitled to something for its risk? Usually we penalize the company and make it stand the loss on its books. Another manufacturing company stood to lose at one time about $500,000 before the induction motor was made a success. It is certainly entitled to a large return for this risk, especially when we consider the enormous value of the induction motor to the world. Similarly, the early transmission companies stood to lose the entire first investments made. And yet, in spite of the enormous value of this pioneer work, we hear many people who say there shall be a return only on the wise investment. Who is to judge what was a wise investment in water power twenty years ago?

(4) If all classes of service were of the same kind there would be little difficulty in arriving at rates that would satisfy the company and the public, but where the same service is used for various purposes, the rates for the service vary, the public is confused and generally considers that it is being treated unjustly. For example, a man using electricity to light his residence pays a rate of say 10 cents per kilowatt-hour, but a man who uses electric power to run an ice plant may get a rate of 1 cent per kilowatt-hour, and usually no amount of explanation will convince the man paying a rate of 10 cents that he is not being robbed. On the other hand, the man paying the 1-cent rate knows that he is getting only a fair rate and the power company is certain both of them are being treated fairly. Because of the confusion that exists in the minds of the consumers, many power companies, especially those supplying lighting to many eastern cities, do not encourage the use of electricity for power, because they believe the lighting consumers will think they should have the same rates, or at least lower rates than are warranted. As a matter of fact, a thorough understanding on the part of the consumer and the offering of the electric service for all purposes, especially for power, will result not only in some reduction in rates to the lighting consumers, but what is much more important, the use of electricity for power purposes will stimulate other industries and these will, of course, make the community more prosperous. A prosperous community or individual is never burdened by the lighting bill, as it is insignificant when measured in terms of the service received and the general benefits derived by the community when it has an ample power supply available and used for all purposes.

Electricity for lighting and power purposes cannot be stored in any large quantities, therefore the plant must at each instant generate the total supply. The lighting consumer must, therefore, have available all day the possibility of instant service, but he may only use the service to produce revenue for the company a few hours each evening. This is the usual explanation given for the higher rates charged for lighting, that is, that the lighting consumer uses the light only a few hours per day, whereas the power user's service extends over the larger part of the day, and also the power consumer uses a much greater quantity. The revenue obtained from a consumer having a 100-h.p. motor may be equal to that obtained from a hundred or two hundred lighting consumers, and herein lies the crux of the entire matter, but the consumer does not see it, so we will try another way of explanation.

If, for example, the total of investment and operating expense to serve all the lighting consumers is equal to the total of investment and operating expense to serve all the power consumers, then plainly the revenue derived from each class of service must be the same in order that each may bear its fair share of the expense of the service. In the average up-to-date light and power system the total energy, generally expressed in kilowatt-hours, consumed by the lighting consumers is very much less than the kilowatt-hours consumed by the power consumers. If the power consumers use five times as much as the lighting consumers, then, on the assumption that it costs as much to serve all the lighting consumers as it does all the power consumers, the rate per kilowatt-hour charged the lighting consumers must be five times as large as the rate charged the power consumer. Generally, however, especially when water power is available, and on account of the large cost of distribution, the cost of serving the lighting consumers is greater than the cost of serving the power consumers, so that a greater difference than five to one must exist in the rates for service.

To use a parallel case for illustration, let us take the railroad service and compare the cost of hauling passengers and freight. Transcontinental freight is hauled by the railroads from the East to California at about $1.50 per 100 lb. To haul 300 lb., or about the weight to be hauled when one passenger and his baggage is carried, will give the railroad a revenue of $4.50. The revenue derived, however, for hauling a single passenger over this distance is more than ten times this amount, and yet the passenger only pays his fair share of the expense. Again, local freight is hauled at 1 cent and 2 cents per ton-mile, whereas the passenger pays 2 to 3 cents per passenger-mile; that is, the passenger pays more to be hauled one mile than is charged to haul a ton of freight one mile. The classes of service and the basis of charge are here entirely different, hence there is no confusion in the minds of the public.

Again, a railroad devotes, let us say for simplicity of explanation, one half the railroad investment and one half the operating costs to freight service and the other half to passenger service. In that case plainly the freight revenue and passenger revenue must be equal in order to be equitable. But the railroad may haul 1,000,000,000 tons of freight at an average return of 1 cent per ton-mile, producing $10,000,000 in earnings, and only carry 400,000,000 passengers one mile. Clearly, in order to produce the same revenue from the passenger as from the freight service, it must receive an average rate of 2½ cents per passenger-mile. On a ton-mile basis in the illustration the passenger pays about twenty times the rate per ton-mile paid for the freight service. And yet there is no confusion in the minds of the public in this instance, mainly because the same unit of charge is not used. If the railroads attempted to put the passenger business on the same basis as the freight, that is, weigh the passenger and charge so much per ton-mile, as in the case of freight, the public would think it was being robbed, but as a matter of fact, the rates are equitable.

As a matter of equity the passenger-mile rate for service is proper and logical and so is the ton-mile rate for freight. Passenger business is a personal service and paid for on a different unit basis and not on a ton-mile basis as freight is hauled.

Now a similar difference exists in the lighting and power service which brings to the minds of the public the confusion as to the reason for the difference in rates for lighting and power.

Plainly if, for illustration as before, we assume that the investment cost and operation cost of supplying energy for power consumers are the same as the cost for supplying the lighting consumers, it follows that the revenue derived from the two classes of business should be the same. But if the total energy consumed by the power consumers is five times that used by the lighting consumers, it is evident that the average rate charged per kilowatt-hour for lighting must be five times the average rate charged for power. That is, if the average rate for power is 1 cent per kilowatt-hour, the average rate for lighting must be 5 cents per kilowatt-hour. If the company sells 500,000,000 kw-hr. for power at an average rate of 1 cent, it will receive $5,000,000 in revenue. But if the amount of energy supplied for lighting is only 100,000,000 kw-hr. the charge must be 5 cents per kilowatt-hour to produce the same revenue.

Always, however, on account of the cost of distribution, the cost of the lighting service is much greater than the cost of the power service, and generally, therefore, we find the lighting rates about ten times the rates for power service. The total investment in the given case, for illustration, may be divided as follows:

Investment for power consumers	$15,000,000
" " lighting consumers, to substations	15,000,000
" " lighting consumers, for distribution	15,000,000

And the earnings necessary so that each may pay its fair share may be as follows:

From power consumers	$3,000,000
From lighting consumers, to substations	$3,000,000
From lighting consumers, for distribution	$3,000,000
Total to be earned	$9,000,000

The power consumers may use	400,000,000	kw-hr.
The lighting consumers may use	100,000,000	"

Fair rates would then be:

For power consumers, charges to substations . . . . $\frac{300,000,000 \text{ cents}}{400,000,000} = 0.75$ cent per kw-hr.

For lighting consumers, charges to substations . . . . $\frac{300,000,000 \text{ cents}}{100,000,000} = 3$ cents per kw-hr.

For lighting consumers, for distribution . . . . $\frac{300,000,000 \text{ cents}}{100,000,000} = 3$ cents per kw-hr.

This would make the total average rate to the lighting consumer 6 cents per kilowatt-hour, and the total average rate to the power consumer ¾ cent per kilowatt-hour. If the kilowatt-hours consumed for lighting are 150,000,000, the rate to the substation is 2 cents per kilowatt-hour, and the total rate 4 cents.

In the above explanation, which the consumer can understand, there is no use of the terms diversity factor and load factor. It puts lighting consumers in one class and power consumers in another, and determines average class rates from the cost of giving service and the amount of energy used by each class of consumer.

It is seen, therefore, that the lighting consumer's rate is much higher than the rate to the power consumer because:

(1st) The investment and cost of operation to serve the lighting consumer are greater than the investment and cost of operation to serve the power consumer, and

(2nd) Much more important, the total energy consumed by the power consumers is much greater than that used by the lighting consumers *for the same peak demand.*

The confusion that exists in the case of the lighting rates comes from charging for the same unit of service. In the freight and passenger rates there is a natural difference in the method of charging, hence there is no confusion. In the lighting and power business there is no such natural method of charging a different unit rate. It has been occasionally urged to charge the power user on a sliding scale of charges, starting at the same rate charged the lighting consumer. If the power consumer made the same demands as the lighting consumer, his rate and total charge would be the same as the lighting consumer up to the substation. The scale of rates charged the power consumer would drop rapidly, in excess of this amount, and his average rate could be approximately the same as it would be under the ordinary power rate schedule. But there is objection to this on the part of the power consumer. It is believed, however, that until some form of schedule of rates or class rates is devised which strikes all consumers alike, there will be difficulty in educating the public as to the reason for the difference in the rates. It is believed that equitable "class rates" as herein described will remove the present misunderstanding.

That low average power rates are necessary for low cost of lighting service cannot be questioned, just as low freight rates are necessary in order to obtain low passenger rates. If an attempt were made, for example, to raise the freight rates per ton to nearly equal the passenger rates, there would be no freight, no business, and consequently no money and no passengers.

In the same way, low rates for power service are not only equitable, but absolutely necessary in these times in order to promote the industries of the communities. If we should attempt to raise the rates to the power consumers, the lighting consumers would soon disappear, as business would become stagnant, because in this modern day general power and low rates are necessary in order to make a prosperous community.

Similarly, the reason for the difference in the "class rates" for commercial and residence lighting may be explained. For example, in order that the commercial and residence lighting may pay equitable proportions, let

Power earnings necessary for commercial lighting = $1,000,000
" " " " residence " . = 2,000,000
Distribution " " " commercial " . = 1,000,000
" " " " residence " . = 2,000,000
Suppose commercial consumers use 50,000,000 kw-hr. per year,
and residence consumers use 50,000,000 " " "
From this we obtain:
Average power charge, commercial....... = 2 cents per kw-hr.
Average power charge, residence......... = 4 " " "
Average distribution charge, commercial . = 2 " " "
Average distribution charge, residence.... = 4 " " "
Total average charge, commercial lighting. = 4 " " "
Total average charge, residence lighting. = 8 " " "

It will be noted that if the energy consumption is doubled the rate will be halved, if the total cost remains the same. There will be further differences between large and small commercial and residence business, but these can be taken into account in a sliding scale. In the same way there will be reason for class rates for certain kinds of power business, depending largely on size of plant and the hours during which power is consumed, and a sliding scale of rates for each class of business.

The general method used in determining class rates for a system is as follows: Divide the total amount of money to be earned by the power and light class by the sum of the peak demands of the two classes. This gives the demand charge per kw. Multiply this demand charge by the peak demand of the class. This gives the total revenue to be earned by the class. Divide this revenue by the kilowatt-hours consumed by the class and we obtain the *average class rate* per kw-hr. An example of this will be given later, and in Fig. 1.

The present general method of determining electric lighting rates is to begin at the consumer and add the cost of reading meter, billing, collecting, etc., to the distribution cost and to this add the cost of power. This is equivalent to what the railroads would do if they tried to determine passenger rates between two points by adding the cost of the sale of a ticket to the cost of the oil required to haul the passenger and to this then add the cost of passenger equipment and proportionate cost of the railroad system between the two points. This method is necessarily subject to errors and tends only to confuse, as it concentrates attention on the infinitesimal items.

Why is it not better to take all the passenger business and determine average class passenger rates for the entire system, by taking the entire cost of doing all the railroad business and dividing this cost among the various classes in proportion to the use of the facilities and operating expenses of the different classes? Similarly, much more accurate and satisfactory results can, I believe, be obtained in determining electric rates by proportioning the earnings necessary to support the entire property between the different classes. The total earnings necessary to support the property can be determined, and the proportionate use of the facilities can be readily determined accurately enough for practical purposes. With these facts and the kilowatt-hour consumption of the different classes known, very fair class rates may be determined. In no other way can I see any satisfactory solution of the rate question, so that the business in all its departments may be built up to the best advantage of all the classes of consumers.

The present method is too much like trying to arrive at the cost of raising chickens by "counting them before they are hatched." A safer and better way is to take the actual results of some chicken ranches over a long enough period of years, so that instead of trying to figure the uncertainties and hazards of each item of the business, they are all summed in the balance sheet.

As we have seen, the cost of railroad service per passenger-mile bears only the remotest relation to the cost per ton-mile for freight, and in a degree the same difference exists between residence lighting and power. Also, the cost of hauling a car of nails is about the same as a car of transformers, but the rate on nails is and must be lower for two reasons, (1) there are more nails hauled, and (2) the value of the service is greater in hauling a car of transformers than in hauling a car of nails. To get the nail business at all, the nails must be hauled at a lower rate, and the fact that they bring in revenue in excess of the cost, makes it possible to haul the transformers at a lower rate than could be done if the rates on nails were raised.

Similarly, the cost of electric lighting bears only the remotest relation to the cost of supplying power. Again, the cost of supplying power service to a sawmill or a planing mill must be lower than for supplying another class of factory. First, because the planing mill man insists that if he gives us his power load he must make some profit, and we must therefore furnish him cheap power or we do not get his business at all. Second, if we do not get the planing-mill business, although it may not be as profitable as some other lines of business, we must increase the rates to the other users in order to make up the revenue necessary to support the property. Hence it is generally to the advantage of the other power consumers that the company take on low class power consumers, if this business pays more than the operating expense and serves to reduce rates in general. Three things must be kept in mind regarding any new business:

First—Some profit must be made for the consumer in order to get the business.

Second—Some profit must be made for the company.

Third—The tendency of the business taken on must be such as to cause a general lowering in rates as volume of business increases.

The early electric companies were organized to supply lighting. It was soon recognized that the plant could take on day power, and increase the net revenue, which meant of course that the investment was more efficiently used. As a result of the power business the rates for lighting have been materially reduced. If some industry, for example, could be established to use the power service from say 12 p.m. to 7 a.m., very low rates indeed could be made to get this business. Any revenue added over operating expense would be so much revenue which could be subtracted from the charges to other consumers, hence, even though this business had to be taken at less than one-half cent per kilowatt-hour, it would, from the standpoint of all consumers, be very profitable business for the company, as the earnings would be largely added to the surplus.

The initiation of the low-price night letters by the telegraph companies is an example of additions to the volume of business with the same equipment, tending to reduce the cost of telegraphic service generally.

An example will probably make this plain, although it is quite elementary to the managers of utility properties. Assume that we have installed a water power plant having a normal capacity of 10,000 kw., and that it has cost, including transmission line and substation, $2,500,000. To make the example as simple as possible we will assume that the company contracts to supply the lighting of a city wholesale, so that the company shall earn 8 per cent on its investment in addition to the operation, depreciation and maintenance charges, etc. The total annual consumption is, say, 15,000,000 kw-hr. The consumer agrees to pay 10 per cent in excess of the rate determined from costs in order to have a margin of safety.

Then for the cost of service we have:

Interest		8 per cent =	$200,000
Depreciation	1.5 per cent		
Maintenance	1.5 "		
Taxes and Insurance	1.0 "	4 "	100,000
Total		12 per cent	$300,000
Operation and management			150,000
			$450,000

$$\text{Cost per kw-hr.} = \frac{45{,}000{,}000 \text{ cents}}{15{,}000{,}000 \text{ kw-hr.}} = 3 \text{ cents per kw-hr.}$$

Adding 10 per cent for safety margin = 3.3 " " "

There is a daytime power load of 45,000,000 kw-hr. annually, available in the same town, that can be supplied from the same substation, with the same power plant and transmission system. However, in order to make a rate attractive enough to get the power load, it is agreed that the power consumer shall pay only 6 per cent on one-half the investment, which necessitates that the lighting consumer pay 10 per cent. Each consumer agrees to pay 10 per cent in excess of the rate determined from absolute costs in order to have a margin of safety. The costs then chargeable to the lighting consumer will be:

Interest		10 per cent of one-half investment,	$125,000
Depreciation	1.5 per cent		
Maintenance	1.5 "		
Taxes, ins., etc.	1.0 "	4 " " " "	50,000
Total		14 "	$175,000
One-half operation and management cost			75,000
Total charge to lighting consumer			$250,000

$$\text{Cost per kw-hr.} = \frac{25{,}000{,}000 \text{ cents}}{15{,}000{,}000 \text{ kw-hr.}} = 1.66 \text{ cent per kw-hr.}$$

With 10 per cent added as margin of safety, rate = 1.836 cent per kw-hr.

The result to the lighting consumer is to reduce the rate from 3.3 cents to 1.836 cent per kw-hr., in spite of the fact that his interest rate has been increased from 8 per cent to 10 per cent.

The rate to the power consumer will be:

Interest		6	per cent of one-half investment	$75,000
Depreciation	1.5 per cent			
Maintenance	1.5 "			
Taxes and ins.	1.0 "	4	" " " "	50,000
Total		10	" " " "	$125,000
One-half operation and management cost				75,000
				$200,000

Cost to power consumer per kw-hr. =

$$\frac{20{,}000{,}000 \text{ cents}}{45{,}000{,}000 \text{ kw-hr.}} = 0.444 \text{ cent per kw-hr.}$$

10 per cent added for safety margin gives rate = 0.4888 cent per kw-hr.

If now a consumer could be found to take the power from 12 p.m. to 6 a.m., when the other two consumers are not using it, a rate could be made by which his interest charge could be less than 6 per cent and still both the other consumers would benefit, as the operation charges would be increased very little.

Except for the cost of water storage, which should be apportioned to kw-hr. output, all charges on a water power plant are demand charges and should be apportioned to peak demands of power and light classes.

Let us take now a typical case as applying to the above plant. The load curve in Fig. 1 may be assumed to represent such a case. Here we have the peak demand of the lighting class equal to 7500 kw. and the peak demand of the power class of 7300 kw. As a result the yearly charges of $450,000 are spread over 7300 + 7500 = 14,800 kw., instead of being spread over the 11,000 kw. of the total peak. As a result the yearly demand charges are reduced from

$$\frac{450{,}000}{11{,}000} = \$41 \text{ (practically) to } \frac{450{,}000}{14{,}800} = \$30.50$$

or the demand charges are reduced practically to 75 per cent of what they would be if there were only one class of consumers. This shows the advantage of the diversity factor 1.35. Now charge each class in proportion to class peak demand (see calculations in Fig. 1). As a result the light consumers pay 7500 × $30.50 = $228,750 of the total and the power consumers pay 7300 × $30.50 = $221,250 for power at the substation.

The average charge for lighting is

$$\frac{22{,}875{,}000 \text{ cents}}{15{,}000{,}000 \text{ kw-hr.}} = 1.52 \text{ cent, and adding 10 per cent}$$

gives 1.67 cent per kw-hr.

Similarly, the average power charge is

$$\frac{22{,}125{,}000 \text{ cents}}{45{,}000{,}000 \text{ kw-hr.}} = 0.49 \text{ cent, and adding 10 per cent gives}$$

0.539 cent per kw-hr.

Here we see the effect of the load factors—the lighting load factor being only 22.6 per cent, while the power load factor is 70.5 per cent. The average load factor is 62.5 per cent. Without the power consumer the rate to the lighting consumer would be

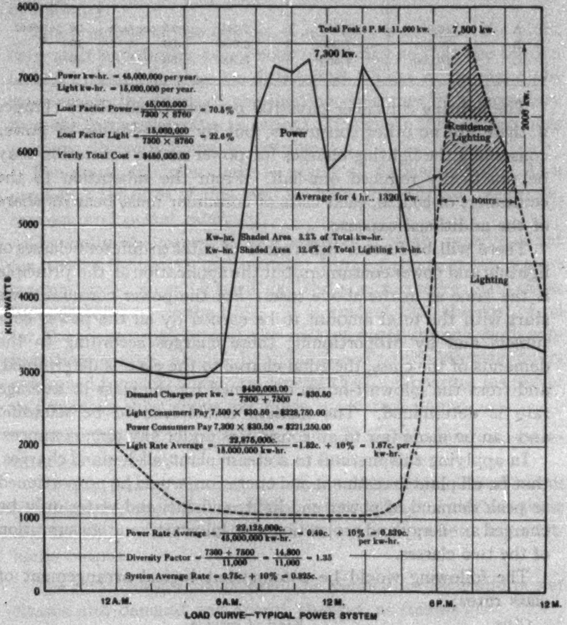

FIG. 1

$$\frac{45{,}000{,}000 \text{ cents}}{15{,}000{,}000 \text{ kw-hr.}} = 3 \text{ cents, and adding 10 per cent gives 3.3}$$

cents; or, in other words, the lighting rate is reduced nearly one-half. Without the lighting consumer the power rate would be 1.1 cent. The mutual benefit is clearly shown by the example.

The following table shows the effect of the power load in reducing the charges to the lighting consumer.

Case	Total peak	Light peak	Power peak	Proportionate charges	
				Light	Power
A	10,000	7,500	2,500	75 per cent	25 per cent
B	10,000	7,500	5,000	60 "	40 "
C	10,000	7,500	7,500	50 "	50 "

The lighting consumer pays 100 per cent of all power charges if there are no other consumers, but by the addition of power consumers the lighting charges for power at the substation may be practically reduced one-half. From the substation to the consumer, of course, each class of consumer must bear its share of the additional expense.

There will be further differences of rates to different classes of lighting and power consumers, but the application of the principle is the same as in the above case. For the power consumers we start with the total amount to be earned by all the power consumers and by proportioning these charges according to the demands of the class, the total charge to the class is determined, and from the kilowatt-hours consumed by the class its average rate is determined. The method is believed to be scientific and can be made fair to all consumers under any circumstances.

In applying this method to a steam plant, all demand charges, that is, all plant investment and operation, would be proportioned to peak demand of power and light, and fuel and water only be charged as energy and proportioned to kilowatt-hour consumption of the two classes.

The following would be a somewhat logical arrangement of class rates:

Class	Kind of service
1	Residence lighting
2	Commercial lighting, electric heating, etc.
3	Street lighting
4	Industrial power or day power
5	Power (24-hour).
6	Power (railway).
7	Power (irrigation)
8	Power (reclamation)
9	Power (off-peak)
10	Power (10 p.m. to 6 a.m.)

It is not intended in this paper to go into the question of the proper rates under each class, but rather to limit the paper to a discussion of the general principles of class rates in such a way as to make clear to the consumer and the investor the necessity and justification for such rates, to the end that there will be a better understanding of the electrical business as an extremely important part of the economic development of any community.

The principle at the bottom of all rates is to make the plant earn all it can during every hour of the day so that the burden of the investment may be distributed. That is, to make the rates within the reach of the lighting consumer, it is necessary to make low power rates in order to distribute the charges over as many kilowatt-hours as possible.

The same principles apply to nearly all public utilities. As a precedent for rates of this kind we have the railroad, telegraph, express, and postal rates.

Generally the power service requires a steam reserve plant for service insurance, and usually, during periods of low water, storage water must be used and the steam reserve plant must be operated part of the time. It is evident that the cost of oil for the steam reserve and the cost of water storage, both representing energy, should be apportioned to the kilowatt-hours consumed by each class. In general the total charges for power delivered to substations are made up in two items:

First: Demand charges, which should include interest, maintenance, depreciation, operation and management.

Second: Energy charges, which should include oil and water for steam reserve plant and the cost of storage water, as these are the only items that should be proportioned to kilowatt-hours output.

The total charges above would be divided for light and power classes into demand and energy charges, as follows:

Light class demand charge =

$$\frac{\text{total demand charge} \times \text{light peak}}{\text{light peak} + \text{power peak}}$$

Power class demand charge =

$$\frac{\text{total demand charge} \times \text{power peak}}{\text{light peak} + \text{power peak}}$$

Light energy charge =

$$\frac{\text{total energy charge} \times \text{light kw-hr.}}{\text{light kw-hr.} + \text{power kw-hr.}}$$

Power energy charge =

$$\frac{\text{total energy charge} \times \text{power kw-hr.}}{\text{light kw-hr.} + \text{power kw-hr.}}$$

Without taking into account the fact that it is the lighting consumer who demands most the service insurance of the steam reserve and who uses the steam reserve inefficiently because it is only used a few hours per day, let us make a few general figures to see what the steam reserve adds to the energy costs of the two classes over those shown by the example in Fig. 1.

Let us assume that the low-water period is three months, or one quarter of the total kilowatt-hours must be supplied by steam power or its equivalent storage water. Let us assume the cost of oil and water for the steam reserve plant at 0.4 cent per kw-hr. and allow the same per kw-hr. for the storage water. Then 15,000,000 kw-hr., or one quarter of the total, must come from storage water or steam power, making a total of $60,000 per year. This will add 0.1 cent per kw-hr. to the total and to each class of consumers' rates, the final rate then being 1.77 cent for the lighting and 0.639 cent for the power.

Adding this 0.1 cent per kw-hr., the *average* rate for power at the substation in the above example is:

$\frac{45{,}000{,}000 \text{ cents}}{60{,}000{,}000} + 0.1 \text{ cent} = 0.75 + 0.1 = 0.85 \text{ cent}$, and adding the 10 per cent for margin of safety, the average rate is 0.935 cent per kw-hr. The average fair lighting rate is, however, 1.77 and the average fair power rate is 0.639 cent.

It is seen, therefore, that the lighting rate is nearly double the average, and the power rate about one-third less than the average rate. It is fallacious, therefore, to apply the average rate for a system to the different classes of consumers, or to different districts or towns. Each class, town or district gets the advantage of the diversity factor (usually about 1.3) for the system, but the rates for the class, town or district should be determined by the method here used.

If a town, for example, has a lighting peak of 100 kw., the lighting consumers in that town must pay $\frac{100}{7500}$ of the total paid by all the lighting consumers on the system. The rate per kilowatt-hour for the town will be determined by dividing the total to be paid by the kilowatt-hours consumed, and therefore the rate per kilowatt-hour depends on the consumers themselves, that is, on how much they consume.

As a check on the above average lighting cost of power, let us see what the average cost of power for the residence lighting would be if supplied by a steam plant. The residence lighting may be taken to extend four hours per day and the following figures, then, are taken from Fig. 1.

Peak load steam plant	2,000 kw.	
Average load " " 4 hours	1,320 "	
Average load " " 24 hours	220 "	
Kw-hr. per year, 220 × 8760 =	1,927,200	
Cost of plant	$200,000.00	
Interest	8 per cent	
Maintenance and depreciation	4.5 " "	
Operation and management, etc.	2.5 " "	
Total cost	15 per cent =	$30,000.00
Energy cost for fuel and water only, 0.5 cent per kw-hr. = 1,927,200 × 0.005 =		9,636.00
Total cost per year		$39,636.00

$$\text{Cost per kw-hr.} = \frac{3{,}963{,}600 \text{ cents}}{1{,}927{,}200 \text{ kw-hr.}} = 2.05 \text{ cents}$$

Demand cost	1.55 cent
Energy cost	0.50
	2.05 cents

The cost of supplying power, therefore, to the residence lighting, will probably average 2 cents per kw-hr. A sliding scale would take care of differences in the individual lighting rate.

The steam plant capacity to take care of the four-hour peak is 2000 kw. or 20 per cent of the entire plant. The kilowatt-hours output is, however, only 3.2 per cent of the total output and only 12.8 per cent of the total lighting load. This brings out clearly the reason for the high unit cost for the consumer taking only a small amount of energy for lighting for about four hours per day.

It is generally known that the railroads prefer the freight to the passenger business, but it is not so generally known that the power companies, at least those having water power, prefer power business to lighting business. And again, commercial business is generally more attractive than residence business. This is evidenced by the fact that certain companies confine their operations to the commercial districts. One of the reasons for this condition is the large amount of capital necessary to serve the small consumer.

Thus it is seen that the attractiveness of the business really varies almost inversely as the rate per kilowatt-hour charged, which is directly contrary to public opinion.

In practise, the difficulty of determining average equitable class rates need not be serious. The most important item is the amount of power consumed by each class, and this can be determined; the item of the maximum demand of each class or the proportionate cost to be charged to each class of business cannot be so accurately determined, but if an error of 10 per cent were made in the example of power and light cost to substations, it would, say, increase the power rates from 0.75 to 0.825 cent, and reduce the lighting rates from 6 to 5.7 cents. An error of 10 per cent in the annual cost of operation would mean an error of $300,000 added to one class and subtracted from the other. The total amount of revenue to be earned can readily be determined, and, if we get the class rates within 10 per cent of the correct amount, there should be no serious complaint.

It is a cut-and-try method, but past practise has already largely determined class rates. The main thing is to have class rates that will develop the business and that will give consumers the right idea of the cost of their class of business, and not have the lighting consumer confused by having his mind on the power rate for an entirely different class of business and supposing that this rate should apply to him.

(5) To get the best results for the company and the consumer, some plan must ultimately be worked out to make an incentive for the company to reduce the cost of the service. At the present time a company may have an obsolete and inefficient engine plant in operation. This stands on the books at, say, $50,000. If this unit is replaced by a modern turbine costing, say, $100,000, the company must wipe off from the books the old engine plant. As a result of the new turbine, the cost of the service is decreased, but generally the effect of this on the company is to have its rates cut. The company has then replaced an old engine by a modern one giving better service, and as a result it has its rates reduced. Of course this state of

affairs does not tend to give the lowest cost of the service, as there is no incentive for the company to improve and reduce the cost of the service. To the credit of most of the large companies it can be said, however, that they have made improvements in spite of this handicap, but the small company generally cannot finance the new improvements.

Again, a community is to be served with electric power. Two plans are feasible, one a local steam turbine plant, the other electric power developed in the mountains and brought to the community by many miles of transmission. The steam power development will cost about one-half the hydroelectric, but the cost of service to the community will be higher if steam power is used. In either case, under present conditions, earnings on the investment are the same percentage. Why, then, go to the mountains and work several years acquiring property, making surveys, getting rights-of-way from a thousand or more owners, if the result to the promoting company is only the additional burden of raising the added amount of capital required—and the consumer gets lower rates?

Of course, under the conditions, there will be only a limited amount of water power developed. To make the water power development attractive there must be an allowance made to produce the incentive to make the water power development. This can be done by an allowance for value of water rights or by allowing a higher rate of return on the investment in water power and the electric transmission of this power to the community.

Economy in construction and operation is much more important than ordinarily assumed, and a company able to get these results should be encouraged. A high-class organization is as necessary as a high-class power system in order to give efficient service. The standard of the business must, therefore, be such as to attract high-class men to the service, and the ability of the company to obtain money must be such as to make it the aggressor in making economies and in obtaining new business.

It costs money to get together a high-class organization and it costs money and energy to keep it together and working efficiently. Different organizations may easily make a difference of 25 to 75 per cent in the cost of construction, and a difference of 5 to 25 per cent in the cost of operation.

It should also be remembered that economy of financing is one of the important elements in low cost of operation. If, through lack of confidence on the part of investors, money cannot be had on reasonable terms, the cost of the service must increase.

The relative value of men to society cannot be expressed as any function of their length, breadth, and thickness, but their value is a function of the saneness and fertility of their imagination, of the confidence inspired by their honesty and ability, and of the results accomplished by their energy and enthusiasm. Similarly, the value of a utility to a community is not capable of full determination by measurement of physical dimensions of structures and the classification of materials, and the fixing of unit prices, and the use of an adding machine. The highest dam or the largest area of reservoir, the longest canal or the longest transmission, do not necessarily give the best power system. The cost of a thing does not measure its value. The boy who spends most money at college does not get the most education. Cashable ideas are not purchased by the pound or cubic yard.

The value of a system is measured by what it does when compared with some other system, and by what the system does for the general good of the community. And what the system does for the general good depends on the ability and honesty of those directing the work, and on the imagination, ability, confidence and the enthusiasm with which the work is done.

To promote the eagerness and ability on the part of the consumer and the company, which is necessary for the best interests of the business, we see, therefore, that ability, brains, confidence, and large experience are necessary, and we cannot get the same results by replacing these with ambition, brag, conceit, and by jumping at conclusions derived from wrong premises and without the test of experience.

All of which, and more, is expressed by the axiom at the beginning of this paper, " The best control of a public utility is that which develops an eagerness and ability on the part of the company to furnish the service, and an equal eagerness and ability on the part of the consumer to purchase the service."

CONCLUSION

It is believed that the success of the electric power business depends upon developing a diversified load. To obtain a diversified load it is necessary to have "class rates," in order that the power business may be developed parallel with the lighting.

Class rates, as determined by the method described in this paper, it is believed, are equitable to all consumers and will result in the lowest rates to all consumers as business is developed.

The eagerness and ability which it is desirable to create on the part of the public utility company and the consumer, then, primarily depend upon two things:

(1) Liberal rates of return on investment so that the companies will make extensions and economies.

(2) Class rates determined by the method herein outlined, applied to develop all the possibilities of the business; and uniform class rates are necessary to build up diversified business, to give the lowest stable rates to all consumers, and to form an incentive to the companies to reduce financing, construction and operation costs.

It is believed that the application of the above will result in "an eagerness and ability on the part of the company to furnish the service and an equal eagerness and ability on the part of the consumer to purchase the service," and it is confidently believed that this will result "to the best interests of the business," considering the company, the consumer and the community as a whole. If it does that, as it is confidently believed it will, there will result "the best control of public utilities."

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THE CHARACTERISTICS OF ELECTRIC MOTORS INVOLVED IN THEIR APPLICATION

BY D. B. RUSHMORE

Abstract of Paper

Industrial power work in the electrical field consists primarily in applying electric motors to the driving of various kinds of machinery. The machines to be driven possess characteristics of different kinds and are run on duty cycles which are often peculiar to the classes of industry involved. Generally the characteristics of the machine to be driven are fixed and the class of motor suitable for this work must be selected with regard to these features.

Motors themselves are adapted to the work of driving machines largely through various forms of controllers. A study of the characteristics of various classes of electric motors in the light of their adaptability to the requirements of the work to be done and a review of certain limitations and mechanical considerations is the object of the paper.

Evolution of the Electric Motor

NEARLY one hundred years have elapsed since A. M. Ampere announced his discovery of the dynamic action between conductors conveying electric currents, this being shortly followed by Michael Faraday's discovery of the principles of electromagnetic induction, which laid the foundation for all subsequent inventions leading to the production of electromagnetic or dynamo-electric machines. Actual industrial motor applications were tried out as early as 1858, the current being obtained from batteries, but it was not until 1873 that the reversible action of the dynamo was discovered by Messrs. Gramme and Fontaine at the Vienna Exposition.

The polyphase induction motor was invented independently by Tesla and Ferraris during the period of 1885-88, and the development of this type of motor has been astonishing. When only a few years ago it was built in sizes of comparatively moderate capacity, we now find units in capacities of 6500 horse power.

STATISTICS

The enormous increase which has taken place during past years in the application of electric motors for driving industrial machinery, is best illustrated by a reference to the U. S. Census Reports given in Tables I and II.

TABLE I

ELECTRIC MOTORS IN MANUFACTURING

	1899	1904	1909
Run by rented power	182,562 h. p.	441,589 h. p.	1,749,031 h. p.
Run by power generated by establishment	310,374	1,150,886	3,068,109
Total horse power	492,936	1,592,475	4,817,140

TABLE II

ELECTRIC MOTORS IN LEADING INDUSTRIES

	1899	1904	1909
Agricultural implements	7,643	20,713	38,905
Automobiles		4,229	41,829
Car and railroad repair shops	4,563	52,635	161,288
Cement		35,292	158,749
Cotton goods	17,594	67,139	235,902
Electrical machinery	24,256	61,753	164,540
Foundry and machine shops	54,907	199,625	623,914
Iron—steel, blast furnaces	8,693	52,610	135,143
Iron—steel, steel works and rolling mills	64,658	254,258	716,609
Lumber and timber products	11,315	33,517	130,707
Paper and wood pulp	2,814	31,604	130,120
Printing and publishing	41,413	93,219	229,312

TABLE III

PRIMARY POWER

	1899	1904	1909
Owned			
Steam	8,139,579	10,825,348	14,202,137
Gas	134,742	289,423	754,083
Water	1,454,112	1,641,949	1,807,144
Other	49,985	98,085	44,742
Rented	319,475	632,902	1,872,670
Total horse power	10,097,893	13,487,707	18,680,776

It is thus seen that at the end of the 10-year period 1899-1909 the use of motors had increased to ten times what it was at the beginning of this period, while in certain industries the increase was even greater. This enormous rate is even more apparent by a reference to Table III, which gives the increase in the primary power used, this being not quite doubled during this period.

ADVANTAGES OF ELECTRIC MOTOR DRIVE

In general, the use of electric motors for driving industrial machinery offers the same advantages for all kinds of applications, the distinctly important features being a decreased power consumption and an increased production for a given equipment.

Among the features which aid in bringing about this condition are:

Centralized power supply.

Simplicity of power transmission and distribution.

Machinery may be conveniently located with reference to production rather than to the power transmitting system.

Changes can easily be made.

Reduced friction losses and thus increased efficiency.

Cleanliness and better light due to the absence of the large number of belts.

Less danger of accidents.

Better reliability of operation.

Wide choice of motors as to size, mechanical design and operating characteristics.

Perfect control, including readiness of starting and stopping and making close speed adjustments.

Remote and automatic control.

The operations may be closely studied by means of recording devices and tests can readily be made.

Economy in time.

Ability to operate any portion of a factory at any time with a power consumption approximately proportional to the work done.

Etc., etc.

APPLICATIONS

The application of a motor to a certain machine involves not only a careful study of the conditions under which the machine is to operate, but also of the characteristics of the motor to be applied to it. The former includes a full knowledge of the duty cycle, the method of drive and the conditions of the location, while the latter covers the important features relating to the operation of the motor itself, including the advantages and limitations of each type.

CLASSIFICATION

Motors may be classified according to type, speed, mechanical features, etc. The types include:

- Direct Current.
    - Series.
    - Series-Shunt.
    - Shunt.
    - Compound.
    - Differential.
- Alternating Current (single-phase and polyphase).
    - Synchronous.
    - Synchronous-Induction.
    - Induction.
        - Phase-Wound.
        - Squirrel-Cage.
    - Commutator.
        - Series Characteristics.
        - Shunt Characteristics.
        - Compound Characteristics.

RATING

In order to correspond as closely as possible to the duty cycle, motors are given different ratings, and the three principal kinds of service which motors are required to meet are:

1st: Continuous duty, where the load is practically constant over long periods of time.

2nd: Cycle duty, in which a definite cycle repeats itself with more or less regularity, the machine stopping after each cycle.

3rd: Varying load duty, in which more or less definite cycles are repeated, but the motor runs continuously.

These last two ratings, for convenience, are combined into a short-time rating and the rating thus derived is simply a calibration of the motor for its particular service, and this refers particularly to heating. The other limitations, such as the commutation and mechanical strength of the heavier part of the cycle, have to be chosen from the duty which the motor is to perform.

LIMITATIONS

The principal limitations in the rating of motors are:

Mechanical strength.
Heating.
Commutation.
Regulation.
Efficiency.

The length of life of the brushes and commutator depends, of course, on the quality of commutation, and for continuous-duty service this should be the best possible. On short-time rated motors some sparking may be permitted without seriously shortening the life of the machine or requiring frequent renewals. Such cases are where the peaks come few and far between, so that the commutator and brushes may have time to convalesce between such sparking periods, due to polishing.

With a geared machine which automatically starts, stops or reverses after a predetermined number of revolutions, such as on planers, etc., the sparking will, however, always occur on the same segments of the commutator, and under this condition sparkless commutation must be maintained on all peaks, or serious deterioration will take place.

Regulation is a more or less important factor in some applications, and for such drives as paper machines, cutting tools, etc., it may be the limiting feature.

The efficiency of continuous-running apparatus is also usually of great importance, while on many types of cycle-duty operation it is of secondary importance, and oftentimes it need not be considered at all. In cases where a motor runs practically all of the time on armature control, or where starting torque and running for a few seconds is the only requirement of the motor, such as a valve motor, the efficiency can be neglected. As a matter of fact, were the motor solely designed for efficiency it would be detrimental, as it would run up the first cost, weight and dimensions with no adequate return.

In general, the power factor of motors need only be considered from the dollars and cents standpoint of supplying current to the motor. While, in general, motors of high power factor are desirable, it is advisable in many cases, and often necessary, to sacrifice power factor for other characteristics for a successful drive.

SPEED CLASSIFICATION

Motors are often also classified with reference to their speed characteristics, as follows:

Constant speed: covering cases where the speed is constant or varies only slightly.

Adjustable speed: covering cases where the speed may be varied over a considerable range, but when once fixed remains at this value, independent of the load changes.

Varying Speed: covering cases where the speed changes with the load, usually decreasing as the load increases.

Multi-speed: covering cases where several distinct speeds may be obtained (two-speed; three-speed) by changing the connections of the windings or other means.

CHARACTERISTIC CURVES

The characteristic curves of different motors must be studied with a view to the application of motors of the proper characteristics chosen to meet various conditions. The torque, starting, running, maximum, may be required to be of very high values in all three, or any one, or any combination. Certain classes of machinery, for example, must have very high starting torque but the running torque may be low, or vice versa.

The characteristic curves usually cover:

Torque (starting, running, maximum).
Current (starting, running, maximum).
Efficiency.
Power factor.
Speed regulation.
Phase characteristics (for synchronous motors).

MECHANICAL CONSIDERATIONS

According to their mechanical features motors may be classified as follows:

Open.
Mechanically protected.
Semi-enclosed.
Totally enclosed.
Enclosed externally ventilated.
Enclosed self-ventilated.
Moisture-proof.
Splash- and waterproof.
Acid-proof.
Submergible.

It is important to know the conditions of location of the motor in order to determine the proper kind of insulation to use. Standard motors are provided with insulation suitable even when motors are operated under conditions of slight moisture. In addition, there are a number of special insulations which are to be used under abnormal conditions, such as:

When windings are exposed to moisture in excess of that for which standard insulation is designed.

For extreme tropical conditions and for use in very hot rooms filled with steam.

When windings are exposed to weak acid or alkaline vapors, excessive alkaline dust, etc. No insulation can, however, as a rule withstand strong acid or alkaline fumes.

When windings are run under conditions which will cause heating somewhat above normal.

When the windings are subject to very high temperatures.

Motors may be of the horizontal or vertical type and connected to the machinery either directly or through belt, chain, rope, gear or friction drives.

The bearings may be of the ordinary journal type, either babbitted or lined with metaline as in cases where the lubrication is liable to be neglected. Of late years the use of roller and ball bearings has also increased rapidly.

OPERATING FEATURES

From the operating point of view there is a large number of features which must be considered in connection with motor applications. Some of these are as follows:

Use of flywheels.

Stability of operation (motors dropping out of step because of short circuits in system).

Effect of voltage variation.

Effect of frequency variation.

Effect of wave form variation.

Effect of unbalancing of phase voltages.

Single-phase operation on three-phase circuits.

Limitations of throwing motors directly on line.

Effect on generating stations, lines and system in general when connecting motors in service.

Reversible service requires motors with small flywheel effect.

Phase advancement for improvement of power factor.

Discussion on "The Characteristics of Electric Motors Involved in Their Application" (Rushmore), New York, February 17, 1915.

The Direct-Current Motor in Industrial Applications

A. C. Lanier: In the field of industrial motor applications, the direct-current motor has been an important factor. The inception of the induction motor, together with the extension of the alternating-current systems of power generation and distribution, seemingly menaced at one time the position of the direct-current motor and has limited somewhat its extension in the industrial field. Competition from this source, however, has tended rather to define sharply the peculiar characteristics and advantages of each motor or system and to direct the growth of each along the most effective lines. In this selective growth, the extreme flexibility of the direct-current motor and its wide range of operating characteristics has offset to an extent the advantages of simplicity, lower first cost, and lighter weight of the induction motor and the considerable advantage in economy and flexibility of the distributing system of which it forms a part.

In industrial motor applications, there is a desired result to be obtained from the equipment as a whole, the useful output of the tool or appliance, in terms of which its effectiveness is measured. In many cases, this output requirement varies widely for a given appliance, and often is not definitely determinable. In addition also to the useful work or output of the tool, energy is consumed in friction losses of the transmission and tool, in accelerating and retarding the masses of the equipment and the motor, in addition to the ordinary operating losses in the motor itself.

In any adequate consideration of direct-current motors in industrial work, attention must be directed both to the characteristics of the motor, and to load requirements of the more important applications in which such motors are used.

Among the more important characteristics and limitations of the direct-current motor must be considered the speed-torque-output relations, commutation, inertia or speed-time, stability, heating and ventilation, efficiency and losses, and constructive features.

Load characteristics met with in industrial applications may be given a general grouping as follows:

(1) Constant output	Non-reversing reversing	Continuous	Constant speed Adjustable "
(2) Varying output	Non-reversing reversing	Continuous Intermittent	Constant speed Varying " Adjustable "
(3) Constant torque	Non-reversing reversing	Continuous Intermittent	Speed constant With armature control Adjustable speed

Speed-Torque Characteristics: With respect to the relation of speed and torque to output, motors are grouped into four classes: constant-speed, multi-speed, adjustable-speed, and varying-speed.

The constant-speed motor is one in which the speed varies only slightly or not at all with change in load. The shunt-wound motor represents this type among direct-current machines. Its speed curve droops slightly with increase in load as indicated in curve *A*, Fig. 1; torque values increase a little more than directly as the output, curve *A'*, Fig. 1. A shunt-wound motor through its relatively flat speed curve and proportional torque output relation finds use in applications not subject to widely varying torque demands, and where change in load should be accompanied by negligible change in speed.

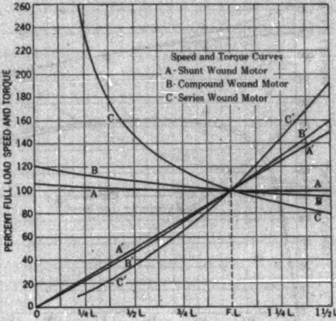

FIG. 1

Line shaft and group drive, centrifugal pumps, and numerous other similar applications make such demands.

The multi-speed motor is one which may be operated at several distinct speeds, the speeds being independent of the load. Such results could be obtained from a motor with double armature winding, from which as many as three distinct speeds may be secured.

The adjustable-speed motor is one "in which the speed can be very gradually adjusted over considerable range, but when once adjusted remains practically unaffected by the load." Its speed characteristic is that of the shunt-wound motor at any adjustment (Fig. 2, curve *A* for low speed, *A'* for high speed). The method of speed adjustment most frequently resorted to is that of varying the m. m. f. of the main field winding by the use of a rheostat connected in series with the winding. The other method is that of varying the reluctance of the main flux path. This may be accomplished by an increase in the effective air gap through the use of adjustable plungers in the main pole, these plungers acting as cores to the main pole and moving along its axis. Another method of varying the reluctance of the main flux path is by axial displacement of the armature from its central magnetic plane.

The adjustable-speed motor is a development of the constant-speed shunt-wound motor in response to demands largely in the machine tool industry. This motor was made practicable, for speed ranges at present used, through the development of the commutating pole. Speed ranges as high as 4 to 1 are readily obtainable. The range of application of these motors has extended widely, not only for general machine tool work but in many definite cycle operations, for example the reversing planer drive, and many drives with constant or some definite torque-speed characteristic. Slight compounding is often given to a motor designed for speed adjustment at its high speed where the torque characteristic of the compound motor is required in the application.

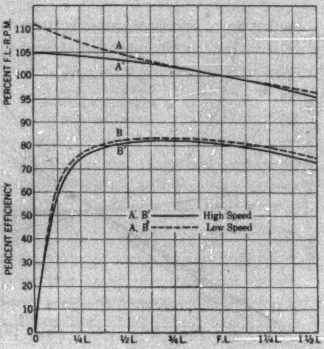

FIG. 2

"Varying speed" covers a class of motors "in which the speed varies with the load, ordinarily decreasing when the load increases, such as series motors, compound-wound motors, and series-shunt motors." The compound-wound motor has a speed curve more strongly drooping than that of the shunt motor, its speed regulation usually amounting to approximately 15 to 25 per cent. In consequence, its torque curve rises somewhat more rapidly with output than in the shunt motor (curves *B* and B', Fig. 1). Its chief use is in service which permits some speed variation with load and where considerable load fluctuation makes the increasing torque characteristic of the compound motor desirable. In many cases this change in speed with load is definitely sought so that the energy in the moving masses, frequently including a flywheel, may serve to limit the load peaks on the motor. Punches, presses and shears fall prominently in the class of applications requiring a compound-wound motor.

In the series-wound motor, the main field winding is connected in series with the armature; the armature flux varies, depending upon the degree of magnetic saturation, more or less directly with the armature current, resulting in a marked rise in torque with increase in output and a strongly drooping speed curve (curve C' and C, Fig. 1). In the series-shunt motor, the larger part of the main field m.m.f. is obtained from the series winding. In general, its speed and torque curves are similar to those of the series motor, though somewhat less marked. The no-load speed of the series-shunt motor will exceed its rated full load speed by approximately 60 to 100 per cent. (Curves B, B, Fig. 3).

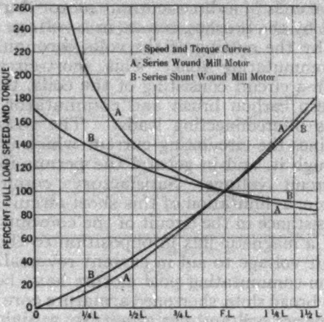

FIG. 3

Series and series-shunt motors are particularly suited for heavy peak load service, especially where frequent reversal with rapid acceleration and retardation are required. The series motor is in general preferred where reduction in load is not sufficient to cause dangerous overspeed and where retardation by plugging is used. If overspeed is possible the series-shunt motor is commonly used and it is also preferable where retardation is secured through dynamic braking. Motors having such characteristics are used in driving roll tables, screw-downs and small rolls in mill work, for bridge, hoist and trolley motions in crane service, and in numerous applications of a similar nature.

Commutation: Commutation was until a comparatively recent period the great limitation to successful operation of the direct-current motor. It is still an important and at times difficult problem on account of the increased severity of duty cycle frequently required, and it constitutes one of the operating limits of the direct-current motor. With reference to the design for commutation, motors may be grouped into three general classes: the non-commutating pole, the commutating pole, and the compensated motor; an important sub-class of the latter is the compensated commutating pole machine.

The non-commutating pole motor: The reversal of current in the armature coils of a direct-current motor during the period of short circuit by the brushes, results in a voltage being induced in these coils by the cutting of the coils through the resultant flux in the commutating zone. This short-circuit voltage is impressed upon a circuit consisting of the coils, the two contact surfaces between carbon brush and commutator, the carbons, and sometimes interconnecting leads. The resistance of this circuit determines the circulating current which a given voltage can force through it, and in general the permissible uncompensated short-circuit voltage. Satisfactory commutation demands, therefore, a limitation of this short-circuit voltage, sufficiently high resistance in the circuit of the commutated coils and where feasible, a magnetic flux in opposition to those generating the short-circuit voltage to aid in current reversal. Tendencies in design of non-commutating pole motors have been in general toward shallow broad slots, shortened armature core lengths, small number of turns per coil and per armature, a high ratio of field ampere-turns for air gap and teeth to the armature distorting ampere-turns, a relatively flat neutral, and carbon brushes of adequate contact resistance and suitable mechanical characteristics. In non-reversing motors, the shift of the commutating coils into the fringe flux from the main pole may assure approximately correct average compensation for one load, the position of brushes remaining fixed; for lighter loads over-compensation results and for heavier loads under-compensation. This is suggested graphically in Fig. 4; curve A represents the average flux density required for flat compensation with straight-line rate of change of current assumed. Curve B suggests the average density of the fringe flux from the main pole in the commutating zone. Approximately correct average value of the flux is obtained at one point only, as X; beyond certain loads, as Y, the resulting flux reverses and assists the sparking tendency. If the speed is increased by field weakening a condition is approached as suggested by curves A^1, B^1, where helpful commutating flux disappears at the much reduced load as at Y^1.

The distribution of this flux over the commutating zone for any load may differ considerably from values which would be ideal for the shape of instantaneous short-circuit voltages in the coils undergoing commutation. Aside from the embarrassment to certain other characteristics which will be pointed out later, the non-commutating pole motor has rather restricted load speed range; also the load speed range for a given motor will have narrower limits in reversing service with neutral setting of brushes than in non-reversing service where brush shift is possible.

The Commutating Pole Motor. In the commutating pole motor the commutation problem is attacked more directly. The conditions conducive to sparking, as outlined in the discussion above, exist potentially in the commutating pole motor; the action of the commutating pole flux prevents this tendency from becoming active. The speed torque producing functions of the commutating pole motor and the means for securing sparkless current reversal are considered separately, each upon the basis of its particular demand upon the design. The main proportions of the armature and the field system can be laid out and such distribution of active material made as will secure the most effective results in the matter of speed-torque, efficiency, ventilation, moment inertia and economy of design without the compromises necessary in the non-commutating pole machine. The commutating pole motor provides small magnetic poles, through which a magnetic flux of approximately the desired value and distribution may be maintained over the commutating zone. The magnetizing winding for this pole is connected in series with the armature; its m.m.f. is therefore proportional to that of the armature circuit to which it is opposed; it exceeds the latter, however, by an amount necessary to drive the required commutating flux through the reluctance of its magnetic circuit (Fig. 5, connections). By establishing at the point of commutation a magnetic field closely proportioned over a wide range to the current commutated and in value such as to give approximately straight-line reversal of current under the brush, the tendency toward sparking is, in theory, eliminated. The number of commutating poles used may either be equal to or one-half

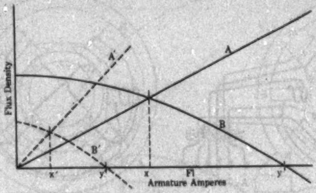

FIG. 4

that of main poles (connections for commutating poles one-half the number of main poles—Fig. 6). If one-half as many commutating as main poles are used, only one side of the armature coil is cutting the commutating flux at a time. Hence each commutating pole must provide sufficient flux for annulling the effects of the short-circuit voltages in the entire coil. The m.m.f. of only that portion of the armature circuit immediately opposed to the commutating pole need be neutralized, however, so that the reduction in the number of commutating poles effects a saving in copper, a corresponding reduction in losses, and an open, more readily ventilated, field structure.

The commutating flux, except in the commutating pole and the gap and tooth section under it, follows paths which are common also to the main pole flux. The distribution of the resultant flux in the magnetic circuit responds to the m.m.fs. of both main and commutating pole windings. The peripheral dimension of the pole should be equal approximately to the width of the commutating zone; the axial dimension is made equal to or less than the armature core length. Where the same number of main and commutating poles is used the commutating pole length is usually less than the armature core length. In the calculation of the commutating pole circuit and winding, the average short-circuit volts per armature coil may be determined on the assumption of a straight-line current reversal under the brush; the density of the commutating flux entering the armature may then be made of such value that there will be generated in that part of the coil cutting by rotation this flux an e.m.f. equal and opposed to the average short-circuit volts. In determining the section of the commutating pole, consideration must be given to the influence of magnetic leakage and saturation as affecting the range of approximately flat compensation.* These effects are suggested in Fig. 7, where values of flux density are plotted as ordinates and current entering the armature and the commutating pole winding as abscissas. Curve *A* represents the useful

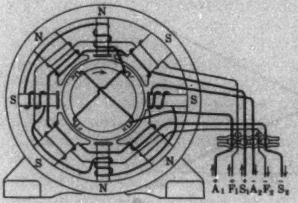

FIG. 5

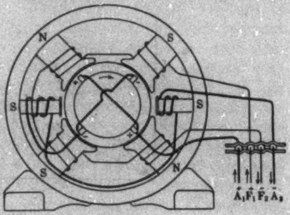

FIG. 6

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*H. E. Stokes: "Commutating Pole Saturation in D-C. Machines", TRANSACTIONS A. I. E. E., 1913, Vol. XXXII, p. 1527.

commutating flux entering the armature, *B* the flux entering the commutating pole at the yoke and *C* the useful flux in the armature for level compensation as determined by the average reactance volts. As indicated, the useful flux reaches a maximum at some load as at *X*, beyond which it decreases, finally reversing at *Y*. The commutating range is limited to a value of current, as at *Z*, beyond which the uncompensated voltage will cause objectionable sparking. A careful consideration of the relative permeance of leakage and useful flux paths, of the m.m.fs. impressed upon each, and of the degree of magnetic saturation of the iron in the circuit of the commutating pole flux, is necessary in order to limit the amount of departure from direct proportionality of useful commutating flux to armature current within such values as will assure sparkless commutation over the desired load range of the motor. Obviously, the approximate proportionality between commutating flux and armature current can be secured over a wider load range, in general, in motors with small number of poles, than in those having many poles.

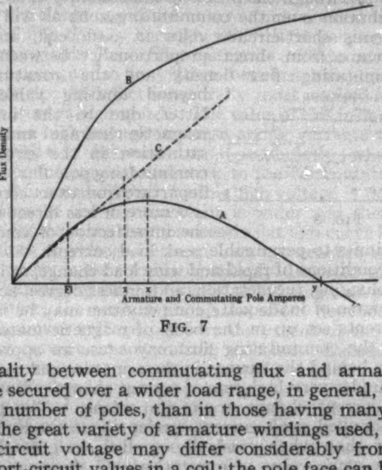

FIG. 7

Due to the great variety of armature windings used, the average short-circuit voltage may differ considerably from instantaneous short-circuit values in a coil; the pole face can be shaped so as to give approximately the distribution desired but some unbalancing of voltage will necessarily exist. These unbalanced voltages bear some relation to the average short-circuit volts per coil and per brush, and to the abruptness of change in instantaneous values of the short-circuit volts in a coil as it moves through the commutating zone. The relation between average and instantaneous values of short-circuit voltage per coil using the usual assumptions is indicated in Fig. 8*; e_r = average short-

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*Brunt: " Auxiliary Pole Design." *Electrical Review and Western Electrician*, 1911.

circuit volts per coil, e_m = max. short-circuit volts, e' = the value of volts in a single coil unaffected by mutual induction of other coils, and b_w the width of the commutating zone. The voltage steps, e', here indicated are relatively small, and fairly regular. In some armature windings the changes in instantaneous value of volts may be larger, and may produce troublesome circulating currents. Experience indicates working limits for these quantities mentioned above, which are serviceable in connection with other factors in predetermining commutation. The volume of current circulating in the commutated coils or carried in an arc as the coils leave the brush is a measure of the damage done to the commutator and carbons; the current capacity of the motor is, therefore, a factor in determining permissible commutating constants.

Failure to attain complete compensation for the short-circuit volts, comes through the practical impossibility of securing such flux distribution over the commutating zone as will annul the instantaneous short-circuit volts in each coil, and through the departure from direct proportionality between the average commutating flux density and the armature current beyond limiting values of the latter, due to the influence of magnetic leakage and magnetic saturation in the circuit of the commutating pole flux. Extent of departure from exact compensation is a more or less direct measure of the imperfection of commutation, and sets limits to permissible peak load currents.

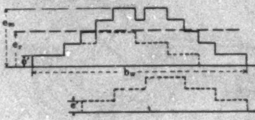

FIG. 8

Under conditions of rapid and wide load change, as in dynamic braking, plugging, regeneration, and, in less degree, acceleration, another source of inadequate compensation may be introduced. Eddy currents set up in the body of magnetic material in the circuit of the commutating flux may cause an appreciable lag of this flux behind the current in the armature and commutating pole field under very high rate of current change. Both rate and range of current change are of importance. The permissible suddenly applied peak current, under above conditions, would be smaller than when gradually applied; in general, approximately the same value of uncompensated short-circuit voltage would fix the allowable peak current in each case. The commutating flux lag can be eliminated, practically, by laminating those parts of its magnetic circuit which materially affect its reponse to change in m.m.f., *i. e.*, the commutating pole cores.

With motors which work over considerable speed range as adjustable and varying speed motors, it is obvious from the foregoing that the speed at which the sudden load change or load reversal, as in plugging or dynamic braking, takes place, is an important factor. The shape of the current curve as well as its instantaneous peak value is of some importance, since the possible damage from circulating currents or spark is a function of its time of duration.

Quickness of response is not always a necessary or even desirable characteristic in the magnetic circuit of the commutating pole. With approximately constant or moderately varying loads, as found in a large proportion of industrial applications, the lag in the average value of flux behind current is not appreciable, and a certain amount of sluggishness in the commutating pole aids materially in smoothing out the irregularities in compensation for the wide range of short-circuit voltage conditions necessarily introduced in commercial machines, through the great variety of armature windings used.

Harmful effects may occur outside of the commutating zone, due to high voltage between commutator bars. This condition exists only in high-voltage machines, and at high speed in some adjustable speed motors subject to wide load speed range. The instantaneous voltage generated in any armature coil is proportioned to the flux density through which it is passing and the speed of cutting this flux. The distortion of flux beneath the main pole causes a rise in voltage between bars toward the saturated pole tip; this effect is naturally most marked in adjustable-speed motors at high speed. The value of this instantaneous voltage may be high enough to cause arcing currents to bridge over the insulation between bars, particularly when small particles of conducting material stick to the commutator. The breadth of the zone affected by this high voltage is dependent upon the shape of the flux curve; it is wider and therefore of more serious consequence the more nearly flat this curve becomes. Limiting values of voltage between bars are reached more frequently, however, in field forms of sharply distorted character. This bar-to-bar arcing results usually in burning and pitting of the commutator; the seriousness of the effect depends largely upon the maximum voltage per bar, the extent of the affected zone, and the current capacity of the machine. Excessive voltage between bars makes a motor extremely sensitive to arcing over between brushes of opposite polarity.

The Compensated Motor. In the compensated machine, a distributed field winding is provided, so connected in series with the armature that its m.m.f. opposes that of the latter and equals or exceeds it in value. In the latter case, an active flux for commutation may be secured. In the compensated commutating pole machine, the compensating winding covers only that part of the armature periphery included within the main pole arc, commutating poles supplying the flux required for commutation. The prevention of field distortion under the main poles has made a field for this type of machine in high-voltage work, particularly where subject to sudden and extreme overloads. The use of distributed compensating windings in direct-current motors has been limited almost entirely to large high-voltage machines in heavy reversing service.

Inertia and Speed-Time Relations: The energy in ft-lb. stored in a moving mass is equal to

$$1/2\ m\ v^2 \tag{1}$$

which may be expressed in the case of rotating bodies

$$1/2\ m\ r^2\ w^2 \tag{2}$$

Since the mass m of the rotating body bears a fairly definite relation to the armature volume the stored energy is proportional to

$$D^4\ L\ w^2 \tag{3}$$

The torque and time of acceleration, also derived from the fundamental relation

$$F = m\ a \tag{4}$$

$$T = m\ r^2\ \frac{dw}{dt} \tag{5}$$

$$t = m\ r^2\ \frac{dw}{T} \tag{6}$$

In equations (5) and (6), the right-hand member is again proportional to D^4L.

In any consistent line of motors, a fairly definite relation exists between the volume of the armature per unit torque and the torque. The curve expressing this relation is a drooping one with respect to increasing torque and convex to the axis of torque. For a given value of D^2L the relation between the values of D^4L and the ratio $\frac{D}{L}$ is of interest; for instance, the value of D^4L, where $\frac{D}{L}$ equals 3, is 2 times as great as that where $\frac{D}{L}$ equals 1. The practical constancy of the relation D^2L for wide range of values $\frac{D}{L}$ is more nearly approached in larger machines and those for short time ratings. It is also of interest to note that although the relation $\frac{D^2L}{T}$ decreases with increase in torque, the value of $\frac{D^4L}{T}$ will increase appreciably. More attention must be given to these factors in large than in small machines, particularly since in general the importance of securing speed and economy is more insistent in large than in small drives.

In many cyclic applications calling for frequent reversal of rotation, the stored energy in the rotating armature forms a considerable proportion of that in the whole equipment, and exerts often a determining influence on the time and torque required for acceleration and retardation; in consequence, it affects materially the commutation and heating of the motor. For example, considering two armatures with the same normal torque rating and speed, one of which has twice the value D^4L of the other, the time of acceleration of the one motor would be twice that of the other, same average accelerating torque assumed; the heat to be dissipated, assuming equal losses, would be doubled also and the period of severe commutating strain prolonged in the same proportion. Should it be required to accelerate the two armatures in the same time the torque in the high-inertia armature would have to be double that required for the other, the commutation difficulties may be considerably more than doubled and the heat to be absorbed or dissipated approximately four times as great.

During the acceleration period the motor has to supply torque for friction and active load in addition to that required for accelerating moving masses. During retardation the friction and active load, if any exists, assist in retarding the moving masses. The amount of stored energy in the moving masses is of particular importance with regard to commutation where plugging or dynamic braking is used. This is emphasized where rapid retardation from a relatively high speed is required; the maximum retarding torque current peak comes at approximately the high speed of the retardation period, the reversal of current is at high rate and the limitations to commutation as outlined under that head are strongly emphasized. Reduction in the amount and duration of this peak is important.

In the foregoing remarks about energy required for acceleration, only energy input to armature was considered; the energy wasted in accelerating resistances may add appreciably to the total drawn from the line and lower the efficiency of the equipment materially.

In other cyclic operations, non-reversing with alternate heavy and light loads, large inertia is desirable in order to limit the range of torque exerted and input required by the motor. Frequently a flywheel is used to provide additional inertia and make possible the application of a motor representing more nearly the average power requirements of the drive. A motor with slightly drooping speed characteristics, usually a compound-wound machine, is desirable for such conditions.

In still other applications, as in continuously running drive with approximately constant or only moderately varying loads, the inertia of moving masses is of slight importance.

Stability: In motors of the shunt type with practically flat speed curve and a relatively large amount of inertia of armature, sensitiveness to sudden change in load, speed or voltage may at times occur. This sensitiveness will be emphasized if the driven machine also has considerable inertia or load characteristics with the equivalent of inertia effects. The condition of instability is marked by a surging of current and speed, settling with varying degrees of sluggishness to a stable condition of speed and torque required by the output. This surging may become cumulative in extreme cases.

The commutating pole motor is rather more susceptible to this tendency than the non-commutating machine if the commutating flux, as is common practise, slightly exceeds that required for straight-line reversal of current. This is due to the demagnetizing effect upon the main poles of the resultant m.m.f. of the coils undergoing commutation. Motors with rising speed characteristics are particularly sensitive with respect to instability, and are usually unsatisfactory unless connected to loads having little inertia and having strongly drooping tendencies. The danger of instability is naturally more marked in motors having a wide speed range, and relatively low internal resistance.

A light series field winding, connected in series with the armature, whose magnetizing effect is proportional, in general, to the tendencies toward field weakening and which will give a consistently definite drop in speed with increase of output, will insure stable operation. Such windings applied to shunt motors are called compensating windings. They have the additional advantage of reducing somewhat the light load field losses and in general improving average efficiency in the average load cycle.

Heating and Ventilation. The heat generated in the parts of a motor by internal losses is an important consideration in the design and operation of motors, on account of the temperature limitations of commercial insulating materials. These losses include the I^2r losses in the electric circuits, the effects of hysteresis and eddy currents in the armature and face of pole due to cyclic variations of flux, and mechanical friction. Extra load losses resulting from flux and current distortion, sometimes difficult of accurate estimate, also occur.

The rise in temperature in different parts of a motor above initial values depends upon the heat added to the part, to the mass and thermal capacity of that part and to the effectiveness of heat dissipation. The dissipation of heat takes place through conduction, convection, and radiation. With constant loss and unvarying conditions affecting the heat dissipation, the rise in temperature, starting cold is a logarithmic function of the time, following the general form

$$c = C\,(1 - e^{\frac{-t}{T}}) \tag{7}$$

where c = instantaneous temperature in deg. centigrade corresponding to the time t,

C = ultimate temperature.

T = time in which temperature would rise to C deg. if no energy were dissipated.

e = logarithmic base.

In curve *A*, Fig. 9, is shown the relation between temperature rise and time in an open motor. The initial rate of temperature rise or slope of the curve, is proportional to the ratio of heat energy added to the machine part in question to its heat capacity. The rate of heat dissipation is not constant but increases with the difference between the temperatures of the heated body and of the medium to which the heat is transferred. The rate therefore increases with time, a constant temperature being reached when the rate of heat transfer equals that at which heat is added. Theoretically this condition is reached for t = infinity; practically from two to six hours is sufficient to bring open motors of industrial type to practically constant temperature, the time varying with size and with features of design.

The cooling of the motor follows the law

$$c = Ce^{\frac{-t}{T}} \tag{8}$$

assuming that the motor is at rest without losses. The cooling curve as indicated in *B*, Fig. 9, is much flatter than the heating curve for the ordinary open direct-current motor, which depends largely upon the fanning action of the rotating armature for the convection currents of cooling air. Where cooling air is supplied from an external source, the convection constants would be more nearly the same when the armature is rotating and when it is at rest, and the curve is steeper.

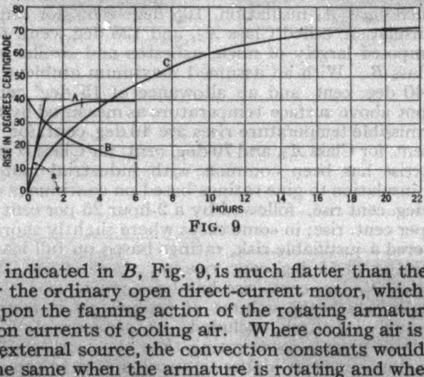

FIG. 9

Factors which enter into the problem of heat dissipation are the resistance to heat flow offered by conducting paths, extent, nature and location of radiating surfaces, and the temperature and quantity of cooling air which can be brought into effective contact with exposed surfaces of heated parts. Practical difficulties and limitations may be suggested as follows. Insulating materials which separate the electric circuits from metal conducting masses offer high resistance to heat flow. Pockets of heated air, due to unfilled spaces in the winding, to the form and location of winding or part in which losses occur, and to the configuration in general of the motor, produce effects analogous to the operation of affected parts in high-temperature air. Rotating bodies also carry around with them a film of air which, becoming heated, tends to interfere with the adequate supply of low-temperature air at the heated surface.

The initial slope of the curve as measured by the angle *a*, in curve *A*, Fig. 9, is proportional to the ratio of the rate of loss heat generated to the heat capacity; the rate of departure from this initial slope is an indication of the effectiveness of heat dissipation. This is suggested by contrasting the shape of curve *C*, Fig. 9, the time-temperature curve of a totally enclosed motor with so called fireproof insulation, with that of curve *A*, for an open motor with fibrous insulation.

Practical limits to operating temperatures are set by the character of insulating materials used, *i.e.*, the temperatures at which damage or too rapid deterioration of insulating papers, fabrics, tapes, inpregnating gums and varnishes will not result. In the Standardization Rules of the American Institute of Electrical Engineers 95 deg. cent. is considered the maximum safe operating temperature for fibrous insulation without impregnation, called class A_1 insulation, 105 deg. cent. for impregnated fibrous insulation, called Class A_2, and 125 deg. cent. for insulations composed largely of mica, asbestos and similar materials, called Class *B*. With an assumed maximum ambient temperature at 40 deg. cent. and an allowance of 15 deg. cent. excess of hot spot above surface temperature as measured by thermometer, permissible temperature rises are 40 deg. cent. for Class A_1, 50 deg. cent. for Class A_2, and 70 deg. cent. for Class *B* insulation. The practise has been common with industrial motors using Class A_2 insulation to give ratings based on continuous operation with 40 deg. cent rise, followed by a 2-hour 25 per cent overload with 55 per cent. rise; in some cases where slightly shortened life is considered a justifiable risk, ratings based on full load continuous operation at 55 deg. cent. rise have been given. For Class *B* insulation 75 deg. cent. rise has been much used.

Motors in which the volume of cooling air is restricted or renewal supply is entirely excluded—*i.e.*, semi- or totally enclosed machines—are given a lower rating than the corresponding open motor or else operate at higher temperatures. In semi-enclosed motors, the proportion of air opening to total area of enclosing cover, and the distribution of openings, are determining factors in the reduction in the rate of heat dissipation. In the totally enclosed motor, the parts of the machine in which losses occur are surrounded by air of relatively high temperature; the external surface of the motor has the function of radiating the heat brought to it from inside by conduction, convection and radiation, in addition to that of mechanical protection. Fig. 10 shows a totally enclosed dust-proof motor in which effective increase in radiating surface is secured through corrugations on the end brackets and covers; in contrast an open motor is shown in Fig. 11, where reliance is placed upon openness of construction for effective

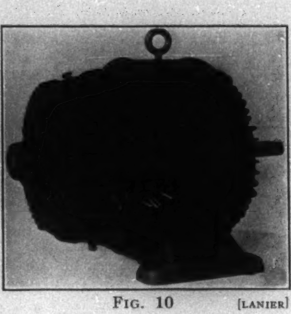

FIG. 10 [LANIER]

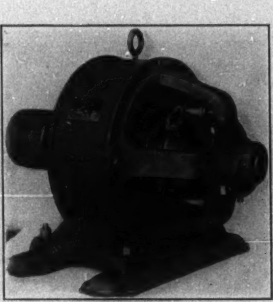

FIG. 11 [LANIER]

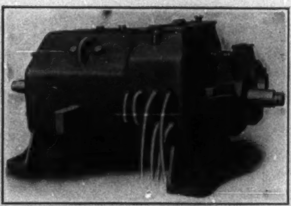

FIG. 13 [LANIER]

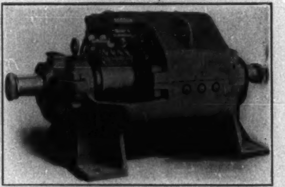

FIG. 14 [LANIER]

heat dissipation. In enclosed motors, the loss in rating may in many instances be offset by artificial ventilation, secured through a fan on the rotor shaft with inlet and outlet in motor shell, or from a fan located externally.

Short time ratings have been much used in motors designed for certain classes of service, as for instance, one- and two-hour ratings for adjustable speed machine tool motors, one-hour ratings for varying speed mill motors, and one-half-hour ratings for crane motors. The rating given is such that the motor will not exceed safe or specified temperature limits when operating at its rated output for the period indicated, the motor starting cold. Such ratings are largely nominal in character. Though often used in intermittent service, with rest periods of sufficiently long duration to allow effective cooling, and with work periods roughly approximating the ratings given, they are, in general, of value as indicating the fitness of the motor for service requiring varying and frequent peak load, and as a basis in applying motors for a known though possibly very different character of cycle.

Motors are applied frequently on a cycle of duty more or less well defined, which repeats itself with some regularity. The losses in the motor would, under such conditions, vary during the cycle, and the rate of heating or cooling change in consequence. Starting cold, the curve of instantaneous temperature values would have an irregularly rising trend, assuming under continuous operation a form corresponding to the cyclic changes in the thermal conditions of the motor. The curve would be made up of elements of the heating and cooling curves of the motor. Where the heating effects of load variations do not lead to wide changes in temperature during the cycle, *i.e.*, the load not varying through excessive range or the time intervals short, it is reasonable to use as a basis for application the average value of the losses during the total working period. The motor can then be selected whose temperature rise for similar losses will not exceed, during the total time of operation, safe temperature limits.

The usual cyclic operation is not sufficiently well defined to admit of accurate predetermination, and irregularities of duty under ordinary work conditions are such as to render too much refinement unwarranted. For such conditions, particularly in the case of motors having relatively flat efficiency curves, the method of application based on the root-mean-square value of the horse power has proved adequate. This effective value of horse power is obtained by multiplying the squared horse power for each period by the time during which it may be assumed constant, summing these products, and dividing this summation by the total time of the cycle including the rest intervals: the square root of this quotient gives the r.m.s. h.p.

From a table or curve for each motor in a line, giving horse powers for different periods of operation, the values determined under thermal conditions simulating those of the average duty cycle, a motor suitable for the estimated cycle can be selected.

Efficiency: The losses in electric motors, both as to quantity and distribution are of importance in their bearing upon efficiency and in the relation of efficiency to output. The relative proportions of variable losses (the I^2R losses in the series path of the machine) and of the constant losses (bearing and brush friction, windage, iron losses, and shunt field losses) determine the shape of the efficiency curve. It should be noted here that the so-called constant losses are not all of them constant; due to distortion in flux and current distribution, additional losses occur on load. The difference in the shape of the efficiency curve in two machines of approximately the same torque and built on the same frame but wound for different speeds is indicated in Fig. 12, curves *A* and *B*. Curve *A* is the efficiency of a low-speed motor with relatively small constant losses, curve *B* for a high-speed motor where the constant losses are relatively large: curve *A* shows naturally higher efficiencies at light loads, curve *B* at higher loads. Such differences in loss distribution are the logical results of designing a line of machines by frames, each frame representing, within average range of speeds for which commercial machines are wound, a given torque capacity which can be exerted under normal operating conditions, and to satisfy specified limitations as to temperature rise. In consequence, the average total flux in the magnetic circuit of a frame differs little for a wide range of speed ratings as secured through different armature windings.

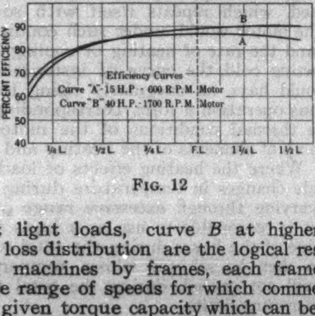

FIG. 12

In adjustable-speed motors, particularly where wide speed range features, the motor efficiency at low speed has the predominance of relatively large variable losses emphasized as indicated in full line curve *B′*, Fig. 2. At high speed, the increase in friction, windage, and iron losses is offset in part by the reduction of those in the shunt field; the variable losses, under the assumption of constant horse power rating, being approximately the same as at low speed, increase slightly where there is decrease in efficiency. The curves at low and high speed are, therefore, similar in shape, efficiencies for equivalent output being, in general, lower at high than at low speed, and the differences more marked at partial than at full load. These differences are most marked in small motors having wide speed range.

In short time ratings, where variable losses are increased, usually to a greater extent than fixed losses, the tendency is in general to emphasize relatively high light-load efficiencies. On the other hand, in enclosed motors for continuous service, due to lowered rate of heat dissipation, the rating is reduced, the variable losses are affected to a greater extent than the fixed losses, and the efficiency curve shows, in general, lower efficiencies for partial than for full loads and limited overloads.

Mechanical Characteristics: Light weight and small overall dimensions are important factors in the ordinary industrial motor, where ease in handling complete motors or replacement parts must be taken into consideration. They frequently are mounted, also, directly on the machines or tools which they drive, their weight supported and their dimensions limited by the structure of the latter. Standardization and interchangeability of parts are essential requirements of the modern motor. The great diversity in the character of industrial motor applications has led also to the development of many different mechanical forms in a line of machines, in many cases without affecting the electrical characteristics; among these might be mentioned vertical, back-geared, semi- and totally enclosed motors, and idler pulley attachments for motors. Certain classes of heavy services, in particular mill and crane work, have led to special features of design, both electrical and mechanical. Electrical characteristics have been commented upon in the preceding pages; in mechanical construction such motors are marked by very rigid frame structures with wide spread of feet, large shafts and ample bearings, small armature diameters, with windings both in armature and field systems braced to stand very severe duty, and frequently in addition are insulated to stand extra high temperatures (Class *B* insulation). Figs. 13 and 14 give a fair idea of constructive features of the enclosed and open motor of the well-known mill type.

To summarize the foregoing characteristics of direct-current motors, and make more definite their bearing upon service conditions, three classes of motor application will be briefly reviewed.

1. The constant, or slightly varying load, constant speed, continuously operating drive, as typified in some forms of line shaft and group drive, blowers, and centrifugal pumps.

2. Non-reversing, continuously running, cyclic duty with alternating peak and partial loads, such as shears, punches, presses and hot saw.

3. Reversing cycles, usually with duty of peak character during the useful work part of the cycle, as in the adjustable-speed reversing planer motor, and the varying-speed mill motor applied on roll tables or screw-downs in steel mills.

In the motor for constant-speed, continuously running drive with infrequent shut-downs and moderate variations in load, the problem of motor design is found in its simplest form; such applications are approached more or less directly in line shaft and group drive, centrifugal, pumps, fans, etc. The operating characteristics of importance in this class of applications are speed-torque, commutation, stability, heating and ventilation, and efficiency. Usually an approximately constant speed motor of the shunt type is required. The commutation problem is not a difficult one, for a commutating pole motor sparkless commutation and the maintenance of good polish and long life to commutator and carbons being required. Stable operation is essential, though danger of instability is not so great as in other classes of motors and loads; a definite drop in speed characteristic will assure stable operation. A motor with particularly good ventilation is in general required. The almost negligible influence of motor inertia on the important operating characteristics, and the freedom from commutation limitations as secured through the commutating pole, make possible the choice of proportions, the disposition of material, and arrangement of windings such as to secure, within economic limits, the best results as to ventilation. The requirements in the matter of efficiency call for high values, in general between one-half and full load.

In non-reversing, continuously running drives, having cyclic load variations between wide limits, the peaks representing large excess over the average duty, characteristics differing somewhat from those given above, and differently emphasized, are demanded. Speed-torque, commutation, inertia, heating and ventilation, and efficiency require consideration. The drooping speed and well-defined torque characteristics of the compound-wound motor are in general sought, both to allow inertia of moving masses to assume part of peak load demands, and also to secure motor peak torque demands by increment in main flux as well as in armature current increase, thus relieving commutation strain, and lowering somewhat the total heating effects during the cycle. The commutating pole motor best meets the requirements of the service. Conservative armature commutating constants, and attention to leakage and saturation in the circuit of the commutating flux so as to secure reasonably level compensation over the entire load range of the motor, will secure satisfactory results. The rate of current change, particularly where there is large inertia of moving parts, is not sufficiently high to introduce the question of sluggishness in flux response. Large inertia in moving parts is of considerable importance. This inertia may be supplied chiefly by the parts of the driven machine, by the motor armature, or by both supplemented by a separate flywheel. Of two machines equal in other respects, that having an armature of high inertia is preferable; but the readiness with which a flywheel of the desired proportions can be applied to any drive, would not justify the sacrifice of other desirable motor characteristics to secure this effect, and the proportions dictated by good design for commutation, ventilation, efficiency and economy should be chosen. The ventilating characteristics of the motor should be good as in the preceding case; the demands in general would be about the same, based on the average value of the losses, since the alternating periods of heavy and light load are of short duration and will not result usually in appreciable variations in temperature. Good operating efficiency requires high values over a wide range of load, and a motor with level efficiency curve is, in general, desirable. Mechanical design characteristic of well-made industrial motors will usually meet all demands of constructive nature.

For the reversing cycle, the reversing planer motor furnishes a good example. The requirements of the service are a cutting speed of considerable range, usually 2:1, and a return speed as high as can reasonably be obtained; a return speed four times the full field or minimum cutting speed is standard practise. During the cutting stroke variations in torque between partial load and double full load value may occur; during return stroke a driving horse power of from one-quarter to one-half the normal rating, in general, may be counted on. The motor is controlled automatically, the control being actuated by the planer platen. It reverses after each stroke, being brought to rest by dynamic braking or plugging, the former preferred, and accelerated to the full cutting or return speed through armature and field switches. It is of first importance that the inactive part of the operating cycle both as to time and energy expended be reduced to the minimum consistent with satisfactory operation and long life, for in economy of production lies one of the advantages of the reversing planer over the belted and other forms of planer drive.

The motor characteristics of interest in this drive are speed-torque, commutation, inertia, stability, heating and ventilation, and mechanical construction. An adjustable-speed motor, usually 4:1 speed range, is used, the most common speed range being 250 to 1000 r.p.m. A shunt-wound motor may be used, as the definition of adjustable speed implies, but slight compounding is preferable, both to secure maximum accelerating torque with reasonable current peaks, and to assist in carrying extreme cutting loads. The advantage of the series winding is particularly marked in that part of the accelerating period which is secured by shunt field adjustment, limiting the current rush and making smooth and rapid the acceleration when the shunt field resistance is cut in in one step, a feature desirable for rapid acceleration and simplicity of control. The commutation requirements are severe, particularly in braking dynamically from the return stroke at maximum speed: a commutating pole motor is of course essential. The peak braking current should be as high as possible, consistent with satisfactory commutation. The rate of change of current is high during the reversal from motor to generator action in braking. Not only must commutating constants of armature be conservative, and wide range of approximate proportionality between commutating flux and armature current be secured, but rapid response of flux to current change is essential. A motor which meets the dynamic braking requirements, will be equal to the commutation demands of acceleration and of the cutting stroke. It is evident that to keep the time and energy of reversal low, inertia of moving masses should be reduced to the lowest economical figure. The motor armature forms a large, usually the largest single item in this inertia, and the selection of armature proportions for low flywheel effect, as outlined in preceding pages, is of first importance. With light compounding as suggested above, the question of stability does not enter. With a shunt-wound machine, however, some trouble from overspeeding at the end of acceleration to high speed is apt to occur, if very rapid acceleration is sought. The work period during which the cycle of operations is repeated, varies in length, interrupted from time to time for adjustment of cut or inspection of work; a rest interval follows during which the work piece is changed, permitting effective cooling of the motor. The thermal conditions in the motor vary widely during the cycle. In general a short time rating is satisfactory. The conditions determining efficiency also vary widely. Not only do actual loads and losses differ greatly in different parts of the cycle, but the proportion of fixed to variable losses shows marked contrast, as, for instance, between cutting peak at low speed, and partial load return stroke at high speed. Operating conditions determine many factors which affect both efficiency and heating, but, in general, the operating requirement for minimum energy expended during the non-productive part of the cycle, affects favorably these characteristics. The mechanical demands upon a motor for this service are more severe than for the continuous drive; the requirement, however, for low inertia favors their easy attainment. Rigidity of design and the secure fastening of windings subject to widely varying torques and to inertia stresses cover, in general, the important special requirements.

Characteristics of Direct-Current Motors for Elevator Service

Albert Brunt (by letter): Requirements of electric motors for elevator service are such that standard industrial motors cannot be applied without some modification, the extent of the modification depending upon the kind of elevator service that is to be maintained. An analysis of those elements of the elevator application that are of interest to the motor designer is of great importance, as it will disclose the principles to be kept in mind when designing this class of motors. The importance of the elevator industry in this country and also the fact that nowadays the great majority of elevators are built with electric drive, make it well worth while to investigate this interesting motor application.

The conditions to be met in different elevator installations vary a great deal. This naturally has led to a division of the elevator machines into different classes. Both in regard to elevator machine and to driving motor this division is based on the speed of the elevator. In regard to the elevator machinery the division can be made in geared and gearless machines, the geared machines to be subdivided again in worm gear machines and helical or herring-bone gear machines. Worm gear machines are used for low- and medium-speed service, helical gear and gearless machines for high-speed service· Under low speed should be understood elevator speeds up to 200 feet per minute, under medium speed 200-400 feet per minute, and under high speed 400 feet per minute and up (maximum 700 feet per minute.)

The motors for elevator application may be divided in the following three classes·

(1) Motors for low-speed service.

(2) Motors for medium-speed worm gear machines and for high-speed helical gear machines.

(3) Motors for high-speed gearless machines.

Although a-c. motors are used extensively for low-speed elevator work and two-speed induction motors even for speeds up to 350 feet per minute, the characteristics of d-c. motors are far more suitable for this application, especially for high-speed work, for which d-c. motors are used exclusively. For this reason this paper will deal with d-c. elevator motors only.

The different requirements can be shown to the greatest advantage for the second class of motors, those for medium-speed worm gear machines and high-speed herring-bone gear machines, for which reason these motors will be considered first.

There are two important requirements to be met during the cycle of elevator operation, *i.e.*, the operation should be smooth, without jerks causing inconvenience to the passengers in the car, and it should be as economical as possible.

For this kind of service (from 200 to 400 feet per minute) the motor is started over a series resistance which is cut out in several steps, followed by a weakening of the field, also in several steps. If a compound field is used this is cut out before the weakening of the field has begun, as a compounding field on the motor, while it is driving the elevator at its normal speed, that is, the weak field speed of the motor, would make the speed change too much with changes in the load, which is undesirable. When the elevator has to be brought to a stop from its normal speed the accelerating operation is reversed. First, the field is strengthened, causing a momentary regeneration; after that the speed is decreased further by decreasing the armature voltage through the insertion of resistance in series with the armature, after which the armature is disconnected from the line and short-circuited over a resistance, thus decreasing the speed further by dynamic braking. This last operation should bring the speed so near to zero that when finally the mechanical brake is applied no jerk is felt in the car. Also for mechanical reasons it is necessary that the speed be very nearly equal to zero when the mechanical brake is applied, as this brake would wear out very rapidly on account of the great many stops if it were to decrease the motor speed materially, requiring a frequent adjustment of the brake shoes. This mechanical brake is a holding brake only, holding the elevator system at rest when the controller is in the off position; it is actuated by a steel spring and released by a solenoid.

An important point to be settled is the amount of speed variation through field control that an elevator motor should have. Without any field control at all the motor for a certain output of course will be the cheapest, but at the same time will require a great number of series accelerating switches, in order to make the acceleration smooth enough, and a great amount of resistance. Furthermore, this kind of acceleration is very uneconomical due to the amount of power lost in the series resistances. Efficient acceleration and retardation is of great importance for an elevator on account of the great number of stops made. Whereas during the run at normal speed the motor has to develop a torque great enough to lift the unbalanced load and to overcome the friction, during acceleration it has, in addition to this, to develop a torque for accelerating the masses, which is very considerable. With an acceleration of 2.5 ft. per sec. per sec. by which a speed of 400 feet per min. is obtained in 2.67 sec. the acceleration force for a weight W is $\frac{W}{32.2} \times 2.5 = 0.078\ W$. At full load the total masses to be accelerated, however, will be approximately 8 times larger than the unbalanced load which is to be lifted, and when it is considered that a torque is also needed for accelerating the revolving masses, the required accelerating torque will come up to nearly double the full load running torque. Whereas most of the time an elevator is running with an average load and this consumes only little power during the run at normal speed, the work to be performed during starting for accelerating the masses is always nearly the same, to which is to be added the variable work for lifting the load. Economy during acceleration, therefore, is most important, more so than a high full-load motor efficiency. The effect of the amount of speed variation through field control of the motor on the economy of acceleration will be shown by a comparison of Fig. 15 with Fig. 16. Fig. 15 shows accelerating conditions for a motor without field control and Fig. 16 for a motor with a speed variation through field control of 2-1. Both motors are supposed to drive the same elevator and thus are of the same horse power with the high speed of the motor of Fig. 16 equal to the speed of the motor of Fig. 15.

In order to maintain a constant increase in speed per time unit during all of the accelerating period the motor torque will have to be constant during this period, which means that with a constant flux the current should be kept constant. This is supposed to be obtained in Fig. 15 by a controller with an infinite number of series resistance steps which will increase the voltage applied to the armature from zero to E proportional to the speed. If the accelerating time be equal to T the power taken from the line during acceleration will be equal to $E\ I\ T$. If efficiency of acceleration is taken to mean

$$\frac{\text{Power consumption by motor armature}}{\text{Total power consumption}}$$

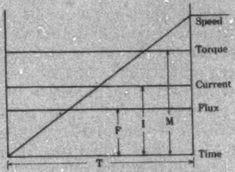

FIG. 15

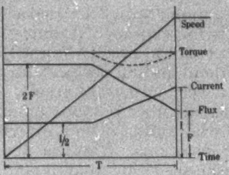

FIG. 16

then in this case this efficiency will be 50 per cent, as the armature power consumption is $\frac{O + E}{2} \times I \times T = \frac{1}{2} E\ I\ T.$

In Fig. 16 uniform acceleration up to half the normal speed is supposed to be obtained by an infinite number of armature resistance steps, same as for the motor in Fig. 15; from half speed to full speed the motor is accelerated by field control, the rate of change of the field being such that the product of current and flux and thus the torque is kept constant. This will very nearly be obtained if the current increases from half to full value and if the flux decreases from full to half strength proportional with the speed as shown in Fig. 16. (This is not quite correct. With current and flux changing as in Fig. 16 the corresponding torque will follow the dotted line, with a maximum difference from the constant torque of 12.5 per cent). The power consumption now will be:
during the 1st half of the accelerating period

$$\frac{T}{2} \times E \times \frac{I}{2} = \frac{1}{4} E\ I\ T$$

during the 2nd half of the accelerating period

$$\frac{T}{2} \times E \times \frac{3}{4} I = \frac{3}{8} E\,I\,T$$

Total $\frac{5}{8} E\,I\,T$.

The armature power consumption during acceleration will be

during the 1st half $\frac{E}{2} \times \frac{I}{2} \times \frac{T}{2} = \frac{1}{8} E\,I\,T$

during the 2nd half $E \times \frac{3}{4} I \times \frac{T}{2} = \frac{3}{8} E\,I \cdot T$

giving a total of $\frac{1}{2}$ $E\,I\,T$ and thus an accelerating efficiency of $\frac{\frac{1}{2}}{\frac{5}{8}} \times 100 = 80$ per cent.

This shows that the power consumed during acceleration of a motor with 2-1 speed variation only is 62.5 per cent of what it is for a motor without speed variation through field control, whereas the accelerating efficiency is 50 per cent for the motor without and 80 per cent for the motor with field control. This is a very important result, as stated already, on account of the great number of stops of an elevator. However, it is not the only advantage of a motor with field control in regard to economy of operation. When in a motor of this kind, running at high speed, the field strength is increased, the motor will momentarily regenerate and thus slow down, the power required for producing this regeneration being taken from the inertia of the moving and revolving masses. Neglecting the motor efficiency, it may be said that the power consumed for producing the torque necessary to accelerate the masses from the full field motor speed up to the high speed, that is, the power converted into inertia of the moving and revolving masses, is returned to the supply line when the motor is retarded from normal to full field speed. This of course is impossible in motors without field control. It is quite an appreciable item, as the inertia increases with the square of the speed. Not only is it true that the acceleration and retardation is much more economical in a motor with field control, but a smooth stop on an elevator running at over 200 feet per minute, with series accelerating switches only, will be impossible. Supposing that the load should be over-hauling the counterweight and thus that the motor should be running as a generator, then if the elevator is to be stopped the introduction of resistance in series with the motor armature will not decrease the speed, but a braking effect only will be obtained when the controller reaches the off position, in which position the armature is disconnected from the line and short-circuited over a resistance, and thus dynamic braking is applied, causing a sudden retardation. The only way to overcome this would be to have, in addition to resistance in series with the armature, switches that introduce resistance in parallel with the armature, thus obtaining dynamic braking during the process of inserting the armature series resistance. This, however, will increase the expense of the controller.

An illustration of the preceding in regard to acceleration economy will be obtained by a comparison of the figures of the following tabulation, taken from actual tests on a worm-geared elevator running at the exceptionally high speed of 450 feet per minute and driven by a motor with 2.5-1 field control.

Number of stops per mile:	24	98	148
Load in car.	Kw-hr. per	car-mile	
150 lb.	1.55	2.55	
750 lb.	1.42	2.41	
1500 lb.	1.70	2.50	3.45
3000 lb.	2.62	3.47	

This shows the strong increase in power consumption with increasing number of stops.

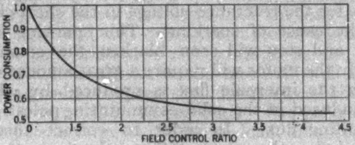

FIG. 17

Fig. 17 gives the power consumption during acceleration for different field control ratios, the amount for the motor without field control being taken as one. This curve shows that in this respect there is not much advantage to use a motor with a field control ratio greater than 2-1, especially where for a certain h.p. and a certain maximum speed determined by the gear ratio, the cost of the motor increases with increasing field control ratio.

The preceding indicates that a motor with 2-1 field control will be the most suitable for this kind of elevator service, which has been proved by actual experience, as a great many motors with this amount of field control have been built and have given entire satisfaction. The question now arises whether these motors should have a compounding winding to be used during armature acceleration only and to be cut out before field acceleration. Due to the fact that only during acceleration and retardation is the shunt field excited by the full voltage, and that the amount of heat developed in the shunt field coils while the motor is running at high speed, and usually also when standing still, is less than 1/4 of what it is at the full field speed, the excitation of the field can be made quite strong so that the magnetic circuit will be rather saturated at full field, making the advantage of having a compounding field in addition to the shunt field negligible. It must be borne in mind that with normal current this motor will have a starting torque equal to two times the normal torque. It would be entirely different if a motor without field control were used. In order to obtain a good starting torque without excessive current the saturation of a motor of this type should not be worked high, so that by using a compounding field during starting an appreciable increase in flux can be obtained, producing the required starting torque without consuming too much current.

Motors for this application of course must be of the commutating pole type and except in one point need not be different from ordinary commutating pole motors for constant speed service. Elevator motors are subject to very rapid changes in the current during accelerating and braking. When the motor is stopped from its normal speed the shunt field is strengthened and the current reverses, producing regeneration. This change in current is so quick that when the interpoles are made of solid material the commutating flux will not change quickly enough to correctly compensate for the reactance voltage in the short-circuited coils which is the cause of sparking. This sparking coming with every start and stop will soon blacken the commutator and consequently the motor will require a great amount of attention. This lag in the interpole flux is produced by eddy currents which are induced in the solid commutating poles by the change in commutating flux. In order to correct this lag in the commutating flux the commutating poles have to be built up from laminations, which is not necessary in motors for constant-speed work in which the current is not subject to quick changes. If the commutating poles are laminated then there is still the magnet yoke as a part of the commutating pole flux circuit which is of solid material and thus must have a damping effect on the commutating flux change. Experience shows, however, that elimination of that part of the lag in the commutating flux which is caused by the solid commutating poles, is sufficient to make the commutating flux change so quickly that it prevents sparking at the brushes, making it unnecessary to also laminate the magnet yoke. The cross-section of the interpoles should be made rather liberal, in order to prevent saturation and to have the right proportion between commutating flux and armature current over the entire range of load.

Whereas the commutating flux circuit should thus be made so as to respond as quickly as possible to changes in the current, the main flux circuit should be made to be rather sluggish so that the change in flux, and thus in speed, when the resistance is introduced in the shunt field circuit, will not be too abrupt. Simplicity of control tends to make the number of steps used for inserting the shunt field resistance as small as possible. In case of motors with 2-1 field control the shunt field resistance often is inserted in one step. Under these conditions the magnet yoke should have the requisite volume to dampen the flux change sufficiently to prevent a too sudden increase in speed causing discomfort to passengers in the car. Whether this effect can be produced by the magnet frame and by the self-induction of the shunt coils depends on the frame dimensions. If the motor is built with a relatively long armature core the yoke volume may be large enough to produce this effect; if not, then there are other ways to produce it. One way is to use a short-circuited turn of rather large copper cross-section around the main field coils, which of course will have a damping effect; another way is to use solid main poles. It also can be obtained by the use in the field circuit of a relay of the fluttering type which strengthens the shunt field when the armature current exceeds a certain value and weakens the field again when the current drops to a certain value.

Of great importance in regard to the proper operation of elevator motors is the speed regulation. The elevator should run as nearly as possible at the same speed independent of the load and whether going up or down. With the car loaded to capacity and going up, the motor will pull its maximum current; going down with same load the load will overhaul the counterweight and will drive the motor as a generator, provided that the gear friction is not so large as to absorb the excess power, which should not be the case with well made gears. The maximum generator speed should not exceed the maximum motor speed by more than 15 per cent. The generator load of course will not be as large as the motor load, on account of guide rail, rope and gear friction. This friction is very considerable, especially the gear friction, so that the maximum generator current can hardly be over 1/3 of the motor current for maximum load.

The following factors of the motor design affect the character of the speed curve: ohmic drop, main field distortion and local brush currents. The ohmic drop in armature and commutating pole winding will cause a decrease in speed as motor and an increase as generator, proportional to the current. The distortion of the main flux will produce a decrease in this flux and thus an increase in speed both as motor and as generator with increasing load. For motors with 2-1 field control, however, this field weakening will not amount to much, as at normal speed the motor has a weak field and consequently the effect of the field distortion is rather small. The influence of both these factors can be calculated with sufficient accuracy; not so, however, with the influence of the local currents. Although it is known how local currents under the brushes affect the main flux and thus the speed, it has not been possible yet to express this effect in mathematical terms. A too strong commutating flux (over-compensation) will produce local currents that have the same effect on the main flux as a backward shift of the brushes, whereas a too weak commutating flux (under-compensation) will cause delayed commutation, the effect of which corresponds to the effect of a forward brush shift. Thus the local currents produced by over-compensation have a main field weakening effect in the motor and a strengthening effect in the generator, whereas those produced by under-compensation have a field strengthening effect in the motor and a weakening effect in the generator. In order to obtain a good speed regulation it will be of advantage to make the commutating flux so that the motor is slightly over-compensated, which will increase the motor speed and decrease the generator speed and thus will decrease the regulation. By adjusting the commutating flux strength for full load current at full field, a slight over-compensation will be obtained at high speed due to the decreased saturation of the magnet yoke. In elevator motors, which on account of the intermittent service have a rather large output coefficient, that is, a high output per unit armature d^2l and thus a large amount of armature ampere-turns, the effect of these local currents is very strong. This is illustrated rather strikingly by the weak field speed curve of a 30-h.p., 425-850 rev. per. min. motor shown by curve *A* of Fig. 18. This curve shows that the commutating pole capacity was too small, requiring a strong interpole excitation which then produced over-compensation at partial load and under, compensation at overload. Curve *B* indicates the speed curve as it would be if affected by ohmic drop and field distortion only. The difference between curves *A* and *B* is caused by the local currents. The speed curve *A* was straightened out by equipping the machine with more liberal commutating poles which produced the speed curve as given by curve *C* of Fig. 18.

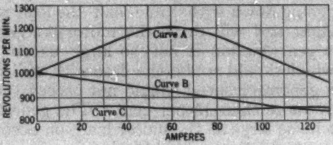

FIG. 18

As stated already, elevator motors are intermittently rated. The normal h.p. of the motor corresponds to the maximum elevator load, so that, except for accelerating and braking peaks, there will be no overload on the motor, on the contrary during most of the time the elevator will be running with an average load nearly equal to the over-balance, which makes the load on the motor very light. The time rating of the motor, therefore, can be taken rather short and varies from ¼ hour to 1 hour. In large office buildings and hotels with continuous service the time

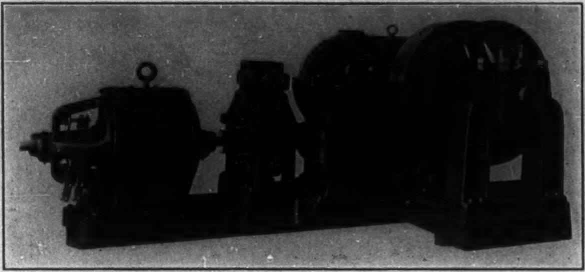

FIG. 19 [BRUNT]

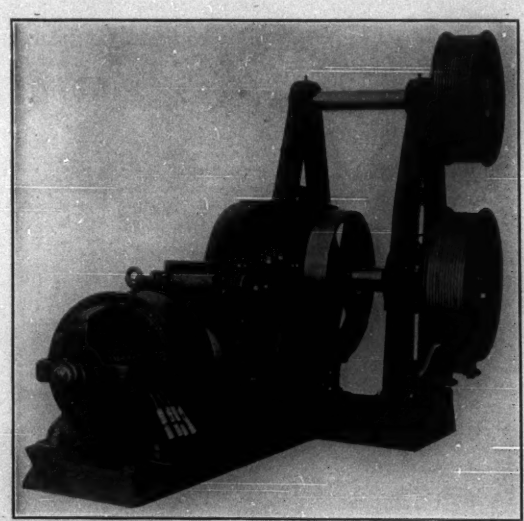

FIG. 20 [BRUNT]

PLATE VI.
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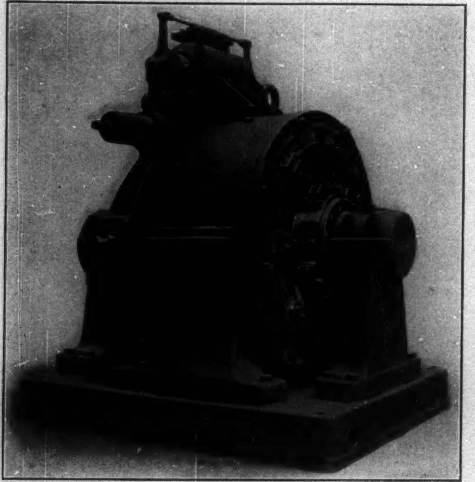

FIG. 23

[BRUNT]

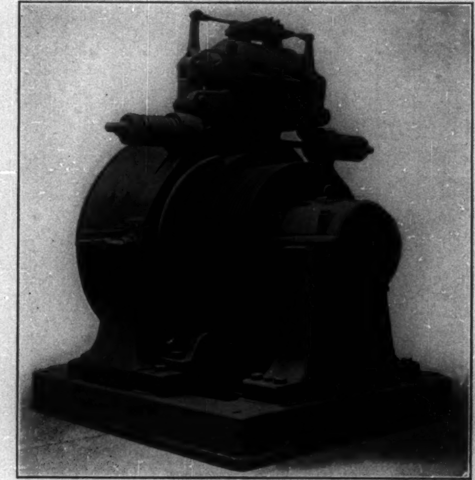

FIG. 24

[BRUNT]

rating of the motor should be taken longer than for elevators with unfrequent service as in small hotels and factories.

The speed of motors driving the elevator drum or sheave through a single or double worm gear should be from 800 to 900 rev. per min., which on a 2-1 field control basis will make the full field speed 400 to 450 rev. per min. With 850 rev. per min. and the smallest gear ratio of 20-1 and a drum or sheave of 36 inches in diameter the car speed will be 400 ft. per min. Lower speeds can be obtained by a larger gear ratio. A slower elevator speed also can be obtained at a slight sacrifice in economy by not running the motor up to its rated high speed. The motor fields should be so designed that the motors can be used for a field control varying between approximately 1.3 and 2.1. This will help the elevator builder out considerably in that he can cover a larger range of speed with fewer gears. Worm gear machines are shown in Figs. 19 and 20.

Worm gears are seldom used for elevator speeds over 400 ft. per min. on account of difficulty with vibration noticeable in the car and with rapid wear. Due to a demand for geared high-speed elevators, during the last couple of years the helical or herring-bone gear has been used in elevator work. It is a well-known fact these gears are very efficient, efficiencies as high as 98 per cent having been obtained. The contact between gear and pinion is of a rolling nature with almost no friction and thus very little wear. These gears when once in alignment will stay in alignment, which is not the case with worm gears, which wear out due to the friction between worm and gear. In order to avoid too large a gear, the gear ratio is considerably smaller than in worm gear machines and varies between 6-1 and 10-1. A car speed of 600 ft. per min. and a sheave diameter of 36 inches will give a motor speed of approximately 400 rev. per min. which with a 2-1 field control ratio will give a motor of 200 to 400 rev. per min. and for this kind of service rated at from 20 to 40 h.p. The limitation in the size of the gear is responsible for a considerably lower motor speed than can be used for motors driving worm gear machines, so that herring-bone gear machines require a more expensive motor. This higher motor cost is not altogether a disadvantage as the low speed decreases the kinetic energy of the motor armature.

It is desirable to build the armatures of elevator motors with comparatively small diameter in order to keep the flywheel effect low. However, the importance of this should not be overestimated, especially not for motors with 2-1 or more field control. With every start an amount of work has to be performed for accelerating the armature, equal to the kinetic energy of the armature at high speed. The kinetic energy is proportional to the square of the angular velocity, so that in case of 2-1 field control motors, $\frac{3}{4}$ of the work to be performed for bringing the motor armature up to the high speed is done while the armature is being accelerated through field weakening. When stopping, this $\frac{3}{4}$ of the total armature inertia is returned either directly or indirectly to the supply circuit. It is returned directly in the case where the motor is being over-hauled, for this inertia is exhausted by regeneration caused by field strengthening. It is returned indirectly in the case where the motor is lifting a load when the inertia stored in the armature will be spent for moving the elevator, thus requiring less power from the supply circuit. Of course not all of the work performed during acceleration is recovered during retardation, because motor efficiency is less than 100 per cent. The relative importance of this loss can best be illustrated by an example.

For an elevator in an average size hotel the total kinetic energy of all moving and revolving parts at balanced load and at the speed of 350 ft. per min. is 15,500 ft-lb. (car weight 2650 lb., counterweight 3650 lb., capacity 2500 lb.) of which 7800 ft-lb., or approximately 50 per cent, are stored in the armature of the 30-h.p., 425-850 rev. per min. motor. This motor has an armature diameter of 14-inches, which is a fairly large diameter for a motor of this size. Of these 7800 ft-lb. armature inertia $\frac{3}{4}$ or 5850 ft-lb. are developed during field acceleration from $\frac{1}{2}$ to full speed. With a motor efficiency of 85 per cent the loss due to this inertia will amount to:

$$\left(\frac{1}{0.85} - 0.85\right)5850 = 0.33 \times 5850 = 1930 \text{ ft-lb.}$$

As 1 kw-hour = 2,653,000 ft-lb., the loss caused by the flywheel effect of the armature for acceleration and retardation between half and full speed will be, per 1000 cycles, $\frac{1,930,000}{2,653,000}$ = 0.728 kw-hr.

This result clearly indicates that in regard to economy not too much attention should be paid to the armature dimensions. A large armature flywheel effect, however, means that the starting and braking current peaks will be larger than for an armature with small flywheel effect, so that in regard to commutation a small armature diameter is desirable. This is especially so for high-speed elevators in large office buildings where a quick start and stop is required, and thus applies to motors driving herringbone gear machines. For medium- and low-speed worm gear machines where quick starting and stopping is not so important, a small armature diameter should not be considered as a too prominent factor.

Quiet operation is another important factor for elevator motors. Magnetic noise in a motor installed at the top or at the bottom of a hatchway may carry far and will be a nuisance to the people in the building. The noise problem is a study in itself on which many papers have been published and will be published, as the final solution has not yet been found. A detailed discussion of this problem would go far beyond the scope of this paper. A large number of armature slots and large air gaps have proved to be effective means for getting quietly running machines.

MOTORS FOR LOW-SPEED ELEVATORS

The service for low-speed elevators usually is infrequent so that economy of acceleration and retardation need not be considered in the first place, but rather first cost of the whole installation and thus of the motor. For a certain h.p. and normal speed the motor without any field control of course is the cheapest, for which reason this kind of motor is the proper one for low-speed service. In order to get a high starting torque without excessive current the motor should have a compound winding, to be used only during starting. This compound winding only can be effective if the magnetic circuit is not saturated when excited by the shunt field alone. It should be of considerable strength, making it necessary to cut it out in two steps before the motor reaches its full speed, so as to get smooth acceleration. These motors are used for single or double worm gear machines; their speed corresponds to the high speed of motors for medium-speed elevators, with some variation. The motors are accelerated by series armature resistance cut out in steps; when stopping the armature series resistance is inserted in steps, after which the motor is very nearly brought to a stop by dynamic braking, the final stop being obtained by an electrically operated mechanical brake.

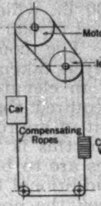

FIG. 21

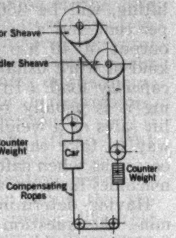

FIG. 22

Motors for High-Speed Gearless Elevators: The tendency to obtain a certain result in the most simple way has led to the introduction of the gearless traction machine for high-speed elevator work. The word traction in connection with this machine is used to indicate that the car motion is produced by the tractive effort of the ropes on the driving traction sheave, whereas in drum machines the car motion is obtained through the winding and unwinding of the ropes on a drum. For high buildings the traction sheave is absolutely essential, as a drum would be of impossibly large dimensions. The gearless traction machines can be divided in two classes: those with 1-1 roping, the principle of which is represented in Fig. 21, which are used for speeds of 500 ft. per min. and above and those with 2-1 roping, shown in principle in Fig. 22, which are used for car speeds up to 450 ft. per min.

The 1-1 traction machine is shown in Figs. 23 and 24 and consists of a low-speed motor to the armature spider of which is bolted a driving sheave. This is in one piece with the brake wheel. The brake shoes are actuated by steel springs and are magnetically released. The idler sheave seen in Figs. 21 and 22 is resorted to in order to get two half turns, equal to one full turn, of the ropes on the traction sheave, which is necessary to obtain the required tractive effort. In order to get a motor speed which is as high as possible the diameter of the driving sheave should be as small as can be without materially affecting the life of the ropes. The smaller the diameter of the traction sheave the larger the strain on the ropes when passing around it. Experience has shown that the smallest allowable sheave diameter for ⅝-in. ropes, which are used for 1-1 traction, is 30 inches. The same motor should be used for the different speeds from 500 ft. per min. up, so that if a 30-inch sheave is used for 500 ft. per min. a 33-inch sheave will give a car speed of 550 ft. per min. and a 36-inch sheave 600 ft. per min. The motor speed at normal elevator speed then will be 64 rev. per min. The maximum load which is to be considered for this kind of service, excepting machines for safe lifting, will be 3500 lb. which at a hoisting efficiency of 88 per cent and a speed of 600 ft. per min. will require a motor output of 40 h.p. The counterweight overbalance for this kind of work usually is taken at from 40 to 45 per cent of the capacity load. In an elevator installation of an office building it is usually required that one machine must be able to lift safes of a weight of approximately 6000 lb. The simplest way to take care of this is to increase the counterweight on occasions when safes are to be lifted, in addition to which these machines have an additional brake for holding this heavy load.

Having determined the normal motor speed at 64 rev. per min., the question arises how much speed variation through field control this motor should have. The motor requirements for obtaining economical acceleration developed for motors driving worm gear machines also apply to gearless motors, that is, the economy of acceleration will increase with increasing field control ratio. However, there are more points to be considered. A look at the worm gear machines as shown in Figs. 19 and 20 will impress the fact that the motor is only a small part of the complete elevator machine, so that an increase of the field control ratio of the motor, increasing the cost of the motor, will only to a small extent affect the cost of the entire elevator installation. For a gearless machine, however, the conditions are entirely different, as a look at the machine of Figs. 23 and 24 will show. In this machine the motor is by far the greatest part of the complete elevator machine, so that an increase in the field control ratio, which will increase the size and the cost of the motor, will materially affect the cost of the complete machine. An increase in acceleration economy, therefore, can only be obtained at an increase in the purchasing price of the machine. This means larger yearly depreciation and interest on the invested capital which may make up for the saving in power consumption during acceleration. There is yet another reason why the field control ratio for gearless machines should be taken lower than for geared machines. Considering only the self-induction of the shunt field coils, in the case of the 30-h.p., 425-850 rev. per min. motor mentioned under worm gear machines it will take 0.45 second for the field to decrease from its full field value to its high speed value if all the resistance is inserted in one step, whereas in the gearless motor with a field control ratio of 1.18-1 it will take the field 0.8 second to decrease from full field strength to normal speed value, which is 85 per cent of the full field strength. In addition to the effect of the self-induction of the shunt coils, comes the delaying effect on the flux change by eddy currents in the magnet yoke. This effect of course is much more pronounced in the heavy frame of the gearless motor than in the light frame of the worm gear motor. If the field control ratio of the gearless motor were increased considerably beyond 1.2-1 this would necessarily increase the time required for the weakening of the field to such an amount that it would be impossible to obtain quick acceleration, a very important item in high-speed elevator work. Whereas in motors driving worm gear machines, means have to be employed to increase the sluggishness of the motor in regard to flux changes, the opposite is true for gearless motors, in which special care has to be taken that the magnet yoke is not too sluggish. A field control ratio of from 1.15 to 1.20-1 seems to be the most favorable.

In designing this gearless motor special attention has to be paid to speed regulation and efficiency and in doing this the heating will take care of itself. A low-speed motor like this necessarily has low no-load losses and a comparative large amount of copper losses, the ohmic drop also being responsible for a considerable drop in speed with increasing load. In order to limit this speed regulation to 15 per cent from maximum load as motor to the corresponding generator load the current density in the armature copper is to be kept fairly low, which at the same time is productive of a good efficiency and low heating. The motor shown in Figs. 23 and 24 has the high full load efficiency of 83 per cent. The partial load efficiencies of course are still higher, which is an advantage in elevator work, where most of the time the load will be below the maximum car capacity.

Due to the low speed the kinetic energy of the motor armature is very small and amounts to only 1620 ft-lb. for the motor of Fig. 23, whereas the inertia of the whole elevator system (car weight 3000 lb., counterweight 4300 lb.) at balanced load and 600 ft. per min. amounts to 20,700 ft-lb., so that the armature only is responsible for 7.8 per cent of the total inertia (approximately 50 per cent in a worm gear machine). This shows that it is no advantage to build the armature of gearless motors with a special small diameter for the purpose of limiting the flywheel effect to the lowest possible value. A large armature diameter and thus a short armature core has the distinct advantage of decreasing the over-all length of the machine and making it possible to build the machines with a large number of poles. This will shorten the armature end connections and thus decrease the ohmic resistance of the armature winding, causing an increase in efficiency and a decrease in speed regulation, both very desirable accomplishments.

The gearless motor referred to in this paper has 8 poles and no commutating poles. Due to the low speed satisfactory commutation can be obtained without resorting to commutating poles, against the use of which there is a serious objection on account of the increase in ohmic drop and thus in the speed regulation, caused by the commutating pole winding.

Compactness and short over-all length are very desirable features for these machines. In order to be able to mount the machines, driving a bank of elevators, side by side, the over-all length should not exceed 6 ft., which will allow enough space between adjacent machines for an attendant to pass between. If this is not done it may be necessary to double-deck the machines, that is, mount alternate machines in two tiers, which of course is undesirable in regard to the cost of the building and accessibility.

The cycle of control of these motors is the same as for worm gear machines except that in addition to the resistance used during acceleration in series with the armature, resistance is also used in parallel with the armature. This last feature produces dynamic braking during retardation before the armature is disconnected from the line and short-circuited through the dynamic braking resistance. This is very helpful in making smooth stops.

Due to a demand for elevators with a speed of from 400 to 450 ft. per min. with larger capacity than is usual for 1-1 machines the 2-1 gearless traction machine has been developed, the principle of which is shown in Fig. 22, and this is being used extensively for department stores. Due to the rope sheave on car and counterweight the speed of the car is half the rope speed, thus permitting the use of a higher speed motor and thus a smaller motor than used for 1-1 roping. As ½-inch ropes are commonly used for this kind of work a smaller traction sheave than in the 1-1 machine can be used. At 450 ft. per min. car speed, 900 ft. per min. rope speed and with a 28-inch sheave the motor speed will have to be 123 rev. per min. Due to the fact that this motor is smaller than the one previously described and thus has a smaller magnet yoke, the field control ratio should be made somewhat larger, 1.3-1 being a good ratio, giving a motor speed of 95-123 rev. per min. The higher speed and the larger field control ratio of this motor necessitate commutating poles in order to obtain satisfactory commutation. The construction of this machine is entirely along the lines of the 1-1 machine and the only reason that it is not used in the place of the 1-1 machine, than which of course it is cheaper, is because the high rope speed, equal to twice the car speed, makes rope wear very considerable. For this reason it is seldom used for rope speed higher than 900 ft. per min., corresponding to a car speed of 450 ft. per min.

APPLICATION OF FLYWHEELS TO MOTORS

K. A. Pauly: The use of flywheels in connection with motors has an important bearing upon the design of the machine to which the flywheel is applied; and further, the design of the flywheel motor unit should properly be a balance between the advantages to be gained by the use of the flywheel and the disadvantages resulting from the special features in the design of the motor necessary to make the wheel effective. The flywheel is a simple and efficient means of storing energy in relatively small quantities and discharging it at a high rate for short periods, and is, therefore, especially applicable to motor applications where the motor is called upon to meet high momentary overloads.

Obviously, one of the advantages to be gained by the use of a flywheel when properly applied is a reduction or practical elimination of the peak demands for power by the motor, which, depending upon conditions, may materially affect the capacity of the generating, transmitting and transforming equipment required for supplying power to the motor, as well as the capacity of the motor itself. To obtain the benefits from the flywheel, however, it is necessary to so design the motor, in connection with which it is used, that the speed will automatically drop through a greater range with an increase in load than is the usual practise for such motors when no flywheel is used.

The simplest methods and those commonly used for obtaining this result are to give direct-current motors an accumulative compound winding and to insert a fixed resistance in the rotor circuit of induction motors. With an equipment of this type, equalizing of the load is only partial except where the peak loads are of extremely short duration and the flywheel large in proportion to the energy required. Where the peak load is sustained for any considerable period the actual reduction in the power demand may be small, and in some cases no reduction may be made, the whole effect of the flywheel being simply to round off the corners of the load curve, unless an excessively heavy wheel is used. Where this is the case, advantage may be taken of automatic means of controlling the field of the direct-current motor or the resistance in the rotor circuit of the induction motor as the load increases, and vice versa, allowing the flywheel to operate through a greater range in speed for the same maximum demand for power by the motor and at the same time obtain a reasonable efficiency over the cycle.

Increasing the speed range through which a motor flywheel unit operates may increase the cost of the motor, lower its efficiency, complicate the control, and have material effect upon the work both as to quantity and quality, while the effect on the flywheel will be to reduce the cost as well as lower the power required to drive it, from which it follows that the design of the combined unit to accomplish definite results, must always be a compromise.

The most common uses of flywheels in connection with motors are those for punch presses, air compressors, which are usually driven by compound-wound direct-current motors or induction motors with fixed high resistance rotors, rolling mills, the motors driving which are controlled by all three methods, and indirectly to mine hoists.

A-C. COMMUTATOR MOTORS

E. F. W. Alexanderson (by letter): There are two distinct reasons for the use of a-c. commutator motors which must not be confused, although both of these reasons may apply for a certain motor application at the same time. The one is that the use of commutators makes it possible to operate motors on single-phase power circuits in cases where high torque starting duty is required. The other reason for the use of commutator motors is the fact that they are adapted for operation at variable speed. The faults of the commutator motors are greater expense and greater maintenance than for either induction motors or direct-current motors, and the use of the commutator motor is not justified unless either one or both of the above-mentioned considerations is important enough to warrant a greater expenditure in the cost of the motor.

As examples of motor types that have been developed to meet the various requirements that come under the above classification the following can be mentioned:

A form of commutator motor is widely used on single-phase power circuits for high starting duty which operates at only one constant speed. The characteristics of this motor are substantially like an induction motor and the principal object of the commutator is to give a high starting torque. Incidental advantages can be derived from the use of commutator by the improvement of power factor. These motors are manufactured in slightly varying forms under various names; but they can, as a whole, be said to have only one function—to provide heavy starting service with single-phase power.

The motor of the other extreme type is the three-phase variable-speed motor. The only essential function of this motor is to provide variable speed with alternating current. In all other respects the induction motor would be preferable, while the commutator makes possible improvements of power factor.

The limitations of starting torque in alternating-current commutator motors are so well known that they are not worth reviewing. It may suffice to say that it is purely a problem of the designer. Motors must be designed so that they will successfully take care of the starting duty for which they are intended. For this purpose the designer must work with rather close margins, and the motors when properly designed do not have the excess starting torque of the direct-current motor.

While in principle the method for speed variation in alternating-current commutator motors is the same as in direct-current motors, there are a number of practical limitations in the design of the motor proper as well as the controlling device, so that a variable-speed a-c. motor has essentially different characteristics from the corresponding d-c. motor with which the operators are familiar. It is important that these differences should be understood by the prospective users of variable-speed a-c. motors because these motors have undoubtedly been barred from a great many useful applications due to misunderstanding between operators and designers of what the real requirements are. An operator who has been in the habit of using variable-speed d-c. motors has naturally grown into the habit of thinking of a variable-speed motor as one with adjustable-speed shunt characteristics, and has possibly been led to assume that it is essential for the successful performance of his service that a motor should have those characteristics. If a prospective motor application is looked into strictly on this basis, the designer must usually give the answer that it is either impossible to meet the requirements, or that the combination of motor and controller would be too expensive to be acceptable. In many cases where these motors have been investigated and where it was believed that an a-c. motor to be acceptable must have the characteristics of a d-c. shunt motor, it was found later that the relations between speed and torque which are characteristics of the simplest form of variable-speed a-c. motor serve the purpose just as well.

A number of important motor applications have been made in this way, for instance, spinning frames and printing presses, and there is no doubt that many more industrial applications of similar character will be found. On the other hand, it is recognized that there are motor applications, such as machine tool drive, where adjustable constant speed is essential. The problem of meeting this requirement with a-c. motors has already been solved in several ways. It is expected that adjustable-speed motors will be found valuable in such cases, whereas the cost will necessarily be a good deal higher than that of the corresponding variable-speed motor with series characteristics. The use of an adjustable-speed shunt motor should, therefore, never be advocated unless it is definitely proved that the simple variable-speed motor with series characteristics would not be suitable.

SYNCHRONOUS MOTORS AND THEIR CHARACTERISTICS IN CONNECTION WITH THEIR APPLICATION

C. J. Fechheimer: For many years the synchronous motor was not looked upon as a desirable motor for the drive of other machinery, nor even for power factor correction, because of three features which were considered objectionable. These were (1) difficulty in starting; (2) the tendency to hunt; (3) the necessity for using direct-current excitation.

Of these three objections, the first was probably of greatest moment. For many years, an auxiliary machine was generally used to start the synchronous machine, and when the motor was brought up to speed, it was synchronized, lamps or a synchroscope being employed. In recent years, however, successful efforts have been made to make the motor self-starting and surprisingly gratifying results have been achieved. It is even possible so to proportion the motors that the starting characteristics in breaking from rest are as good as those which obtain in squirrel cage induction motors for the corresponding ratings. As will be subsequently pointed out, it is not always desirable to secure such starting characteristics.

The application of squirrel cage windings to laminated pole rotors, or the use of solid poles, not only secures good starting characteristics, but also practically eliminates the tendency to hunt. In fact, when modern synchronous motors are installed, little or no thought is given to the hunting tendency. This improvement in synchronous motor operation is partly due to the use of steam and water turbine drive for generators and to improved transmission line design.

Most of the large stations have direct-current busbars, so that no additional equipment is needed to excite the synchronous motors. In installations in which there is no source of direct current immediately available, the exciter is frequently direct-connected to the synchronous motor, and the exciter and the motor are started as one unit. By the time the synchronous motor reaches synchronous speed, the exciter will have generated sufficient electromotive force to excite the fields of the synchronous motor. This also applies to synchronous motors driving direct-current generators, in which case the generated direct electromotive force, if not too high, may be used as exciting electromotive force.

In order thoroughly to understand the applications of synchronous motors, we shall point out the limitations in ratings and capacities, and in order to indicate the advantages which may be obtained by use of synchronous motors in some applications, we give a set of curves of the motor's characteristics.

The synchronous motor, as its name indicates, necessarily runs at constant speed, after it has been synchronized. No developments up to the present time have indicated that it is at all adapted for use as an adjustable-speed motor. One of its advantages is that its speed remains fixed, irrespective of the load or excitation, until the breakdown point is reached, assuming constant frequency. Like the induction motor, but unlike the direct-current motor, the breakdown point in torque depends upon the proportions in the motor, upon the load which has been applied, and upon the impressed electromotive force. Unlike the induction motor, however, there is no falling off in speed up to the breakdown point, and the pull-out point in regard to load can be altered, not only by the magnitude of the impressed voltage, but also by the amount of exciting current. Most commercial synchronous motors are so designed that they will have approximately double normal torque at the pull-out point, when the excitation required for normal operation is applied. It is seldom that more than this is demanded.

While the starting torque of the synchronous motor may be made equal to that of the squirrel cage induction motor, the torque falls off rapidly as synchronism is approached, as will subsequently be pointed out. Hence, if the motor is to start certain kinds of apparatus which demand large torque near synchronous speed, such as fans, or centrifugal pumps, this characteristic may be one limitation.

In the synchronous motor, as in nearly all electrical machinery, the principal limitation other than magnetic saturation is temperature rise. If the motor is to be used for power factor correction, it frequently happens that it must be made larger than would otherwise be necessary, owing to the limitation imposed by the temperature rise of the field coils.

If the field coils are insulated between turns or to ground with organic fibrous material, such as paper, cotton, or linen, it is important for the operator to observe the temperature rise in them, especially if the tendency is to over-excite them. He may conveniently note the change in voltage required to send the exciting current through the field coils, and therefrom calculate the temperature rise. If non-combustible material such as mica or asbestos is used for insulation in the fields, the operator need not be alarmed regarding the temperature rise of that member, except in so far as the stator temperature may have been influenced thereby. If the stator be insulated with fibrous material between turns or to ground, it is important that temperatures below the charring point of such insulation be maintained. Otherwise, a serious breakdown and short-circuit may occur, resulting in temporary disuse of the apparatus. In the smaller sizes of synchronous motors, rotor temperature rise is usually a very serious limitation; so much so, that up to approximately 75 h.p., the induction motor is smaller and cheaper. It is also considered an extra complication to have direct-current excitation for small units. The field of application of small synchronous motors is consequently limited.

CHARACTERISTIC CURVES

The most useful curves, and also those which are most easily determined from test, are the open-circuit saturation and short-circuit curves. To these should be added in order of importance the zero power factor saturation curve, with leading current. From these the load saturation curves at other power factors may be determined. In Fig. 25 are shown these, as well as the lagging current zero power factor and core loss curves. From the saturation curves we may read the exciting current required for the load and power factor corresponding to normal impressed voltage. In Fig. 26 are drawn *V* curves which show the variation of alternating current with exciting current. On these, curves may be plotted along which the power factor is constant. In Fig. 26 are shown the minimum current, or approximately unity power factor, the 80 per cent leading and 80 per cent lagging power factor curves.

The other curves which are of value are those which pertain to synchronous motors during starting. In a paper* by the author published nearly three years ago, Fig. 7 illustrates the characteristic curves during acceleration with fields short-circuited and with squirrel cage winding. Fig. 8 shows similar characteristics with fields open-circuited and with squirrel cage winding. Fig. 9 gives results obtained with squirrel cage winding removed and fields open-circuited. These curves illustrate the marked effect of the squirrel cage winding in producing torque. In Fig. 10 are plotted curves of a solid pole machine without squirrel cage winding and with fields open. All of these curves show that the torque drops off just before synchronism is reached. In order to increase the torque near synchronism, a

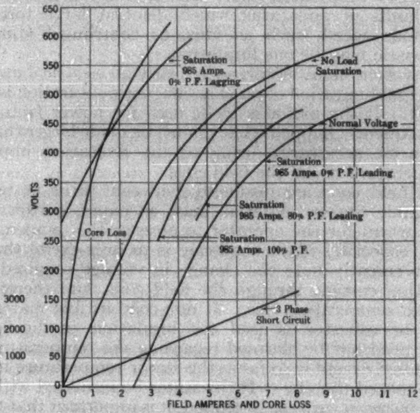

FIG. 25

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*"Self-Starting Synchronous Motors," by C. J. Fechheimer. TRANSACTIONS A. I. E. E. 1912, Vol. XXXI, page 529.

small amount of direct current may be caused to flow in the fields, which may be of material assistance. Figs. 11 and 12 show the effect thus secured, and indicate that there is a certain critical value which will produce a maximum torque at a definite speed, and that to obtain such maximum torque, the direct current should be increased as the speed increases. Below a certain speed any value of direct current decreases, instead of increases, the torque. It is interesting that a synchronous motor will lock into synchronism, if the load be not excessive, without any excitation, and will then run as a synchronous motor receiving alternating-current excitation from the stator.

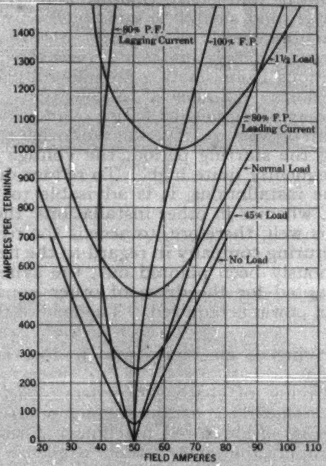

FIG. 26

Oscillograms Figs. 2 to 5,in Mr. F. D. Newbury's paper*, when studied in connection with Figs. 7 to 12 from the author's former paper, convey a clear picture of the phenomena from stand-still to synchronism, of the transients produced by the varying reluctance of the magnetic circuit due to projecting poles, and those caused by temporary changes in connections. There may be a tendency of the synchronous motor, when its fields are short-circuited, to refuse to accelerate beyond half speed. The remedy lies in opening the field circuit, after which the motor will usually accelerate without further difficulty.

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*"The Behavior of Synchronous Motors During Starting." A. I. E. E. TRANSACTIONS, 1913, Vol. XXXII, page 1510.

OPERATING FEATURES

It is now general practise to start synchronous motors by applying to the stator, voltage lower than normal. This is generally accomplished by means of auto-transformers from which suitable taps are brought out. The connection is usually made through oil switches at the switchboard. It is possible, however, when lowering transformers are installed, to bring taps from the secondary windings of such transformers, and start the motors directly therefrom. In a few limited applications, even with motors up to 500 h.p., when such motors are low-speed, it is possible to omit entirely the auto-transformers and throw them over directly on the line. This practise is not generally recommended, however, and should be employed only with the sanction of the manufacturers. It is seldom essential to have more than one starting voltage, it being generally satisfactory to change connections from starting to full voltage, without any intermediate steps. In special applications, however, the manufacturer may recommend the use of intermediate steps, in conjunction with preventive impedance or other suitable arrangement. During the starting period, the voltage induced in the field coils is frequently quite high. To reduce danger from this source, in some installations, it is advisable to have the fields short-circuited, whereas in other installations the fields may be left open. It is well, therefore, to accept the recommendations of the manufacturing company in regard to the field connections.

As has previously been pointed out, the synchronous motor is not well adapted for the drive of other apparatus, when a small amount of power is required. The field of the synchronous motor lies:

1. In the driving of machinery which does not require any speed adjustment.

2. In the driving of machinery where constant speed (as is consistent with nearly constant frequency) is important.

3. In the driving of low-speed machinery, for which induction motors are not applicable, due to their large size and low power factor.

4. In its ability to compensate for reactive currents of other apparatus on the system. When thus used, mechanical power may or may not be supplied.

This leads to a new classification, in which we shall endeavor to outline more specifically the kinds of machinery for transmission schemes in conjunction with which the synchronous motor should be operated.

(*a*) The synchronous motor may be used to drive line shafting when the starting torque required does not exceed about 50 per cent of the normal rating of the motor.

(*b*) The synchronous motor may be used to drive centrifugal pumps or fans when the pull-in torque demanded near synchronous speed does not exceed approximately 40 per cent of the nor-

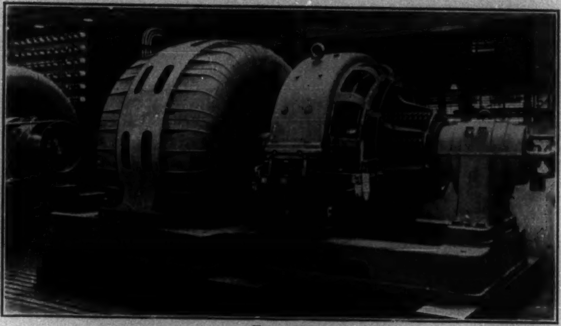

FIG. 27 [FECHHEIMER]

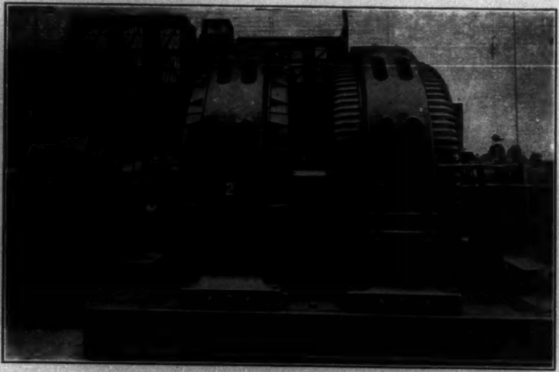

FIG. 28 [FECHHEIMER]

PLATE VIII.
A. I. E. E.
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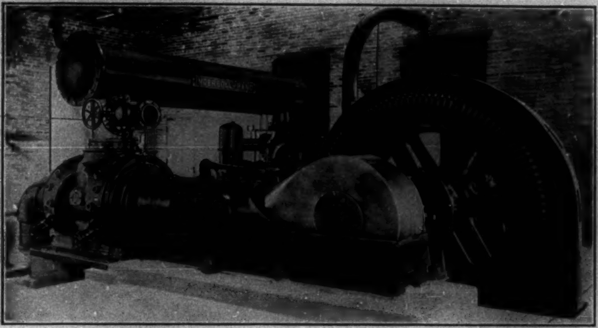


FIG. 29 [FECHHEIMER]

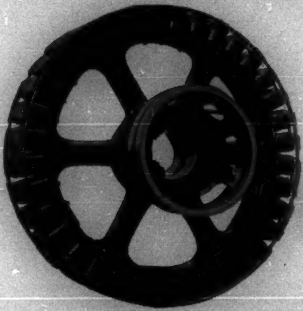


FIG. 30 [FECHHEIMER]

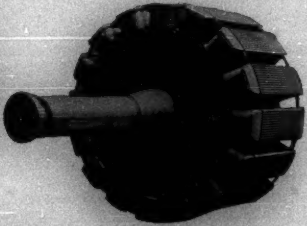


FIG. 31 [FECHHEIMER]

FIG. 32 [FECHHEIMER]

mal rating of the motor, and use is made of a suitable low-resistance squirrel cage winding which decreases the starting and increases the pull-in torque.

(*c*) The synchronous motor may be used to drive direct-current generators in motor-generator sets, especially in the larger sizes.

(*d*) The synchronous motor may be used in conjunction with another synchronous machine, as to form a part of a frequency-changer set.

(*e*) The synchronous motor is especially adapted for the drive of low-speed air compressors, since these generally require about 15 to 20 per cent of normal torque for breaking from rest, and there is seldom difficulty experienced in pull-in torque requirements; furthermore, an induction motor for such low speed has very poor power factor.

(*f*) The synchronous motor may be operated idle for power factor correction only, in which case it is generally given the name of synchronous condenser.

In any of the classifications from (*a*) to (*e*), inclusive, the motor may or may not be used for power factor correction. It may be operated at unity power factor or at leading power factor, depending upon service conditions. It should be understood that if the motor operates at leading power factor it must be suitably designed for carrying the increased current in the field coils, as well as in the stator coils. The ability not only to operate at unity power factor, but also to compensate for the lagging currents of other apparatus on the system is one of the most valuable features of the synchronous motor. If the motor is used as a synchronous condenser only, it is frequently found advisable to operate under-excited, with lagging current, when the load on the line is light, to compensate for the charging current in the transmission line. By means of suitable automatic voltage regulators, the excitation of the synchronous condenser may be adjusted with the load to maintain constant voltage at the receiver end of the line, or to secure such a load-voltage curve as may be found most desirable for the transmission service.

In Figs. 27 to 32 inclusive, are shown some modern types of synchronous motors in various applications. Fig. 27 shows a 1000-kilowatt motor-generator, the motor being wound for 11,000 volts, three-phase, 60 cycles, 514 rev. per min. Fig. 28 shows a synchronous frequency-changer used for transforming 25-cycle, 6300 volts, three-phase power to 62½-cycle, 2700 or 5400-volt, two-phase, and is rated 2500 kilovolt-amperes and operates at 375 rev. per min. Fig. 29 shows an air compressor driven by a synchronous motor, and Fig. 30 shows the rotor of a synchronous motor used for air compressor drive. Fig. 31 shows the rotor of a synchronous condenser for a 15,000-kilovolt-ampere unit, and Fig. 32 synchronous machines which may either be driven by waterwheels, or operated as synchronous condensers for power factor correction.

SPEED REGULATION

F. B. Crosby: Any investigation or discussion of the operating characteristics of electric motors which overlooks speed regulation is hopelessly incomplete. The importance of this factor is so thoroughly appreciated, however, and the characteristics of the more common types of motors so well known, that were it not for material progress during the past year in more satisfactory methods of control I should consider an apology due the members of the Institute for speaking on this time-worn subject.

All motors, whether designed for operation on alternating- or continuous-current circuits, readily fall into three distinct divisions when classified on the basis of speed characteristics.

1st: Constant speed, that is, speed virtually constant, independent of changes in load. The compound-wound continuous-current motor and the synchronous and squirrel cage induction alternating-current motors are typical of this class.

2nd: Variable speed—that is, speed constant for any given load but varying with changes in load. The series d-c. machine with armature control and the induction motor with phase-wound rotor and external secondary resistance illustrate this class.

3rd: Adjustable speed—that is, speeds adjustable over wide range at will of operator, each speed being constant, independent of load fluctuations. The one motor which as a single unit will fully meet these conditions is the d-c. shunt-wound motor with field control.

For the a-c. representatives of this class it has been necessary until recently to accept a compromise in the form of a so-called multi-speed, changeable pole, induction motor, or the more complex arrangement of two such motors in concatenation.

With the exception of certain machine tools which require strictly adjustable speeds throughout a wide range, and such applications as cranes, elevators, small hoists, etc., for which variable-speed motors are usually satisfactory, the great majority of industrial applications are successfully met with a constant-speed motor.

The many excellent characteristics of the induction motor together with the unquestioned advantages of a-c. systems of distribution have led to its general adoption even in many instances where, from the standpoint of speed control alone, a d-c. motor with shunt field control would have been preferable.

There is still a large and more highly specialized field in which the strictly adjustable-speed motor must be employed for one or more of the following reasons. First, in certain processes as, for example, the finishing passes of mills rolling metal in small sections, sudden fluctuations in speed render it impossible to produce a uniform gage, which obviously results in loss of production. Again, it is often desirable to roll the metal at a higher speed than is permissible for entering the pass. It is therefore desirable and often imperative that the speed characteristics of the driving motor shall be such that when the load falls off as the billet leaves the rolls the regulation of the motor will not permit its speed to increase automatically to values which render it impossible to enter the next billet.

While variable-speed motors, such as the series d-c. with armature control or the induction motor with wound rotor and rheostatic control, may be satisfactory under certain conditions for driving mine fans, centrifugal pumps, centrifugal compressors, etc., so far as speed control is concerned, their operation at reduced speed over long periods is accompanied by excessive power consumption due to the low efficiencies inherent with armature control.

For such applications it has been necessary to resort to continuous-current motors with shunt field control, though it is evident that ample incentive exists for the development of a simple, efficient and commercially practicable adjustable-speed a-c. motor. The problem is to design one.

Much has been done both in this country and abroad along this line, and the results obtained indicate an early solution of the problem, at least in motors of relatively small capacities.

In a short paper on "The Economic Speed Regulation of A-C. Motors for Driving Mine Fans" presented at the annual meeting of the Mining section of the Institute in Pittsburgh in April 1913, I had the pleasure of describing briefly a system of adjustable speed control for induction motors which, originally developed abroad, has been modified and perfected to meet American requirements. To distinguish it from armature or rheostatic control this system was then designated and will be referred to as dynamic control.

Since that time nineteen of these auxiliary speed-regulating equipments have been or are now being installed and are in successful operation for driving mine fans and main rolls in steel mills. One of these equipments makes use of the synchronous converter method mentioned below; the remaining eighteen involve a somewhat simpler equipment in which a three-phase commutator motor replaces the auxiliary rotary and d-c. motor of the former method.

Both methods are applicable to induction motors with phase-wound rotors and each accomplishes practically the same results, viz: strictly adjustable speed control of the main induction motor at relatively high efficiency and any desired power factor up to unity or even leading, throughout the range of speed for which it is designed.

Broadly speaking, the commutator motor method is the less expensive for 60-cycle equipments requiring speed regulation up to 30 per cent or for 25-cycle equipments requiring regulation up to 50 per cent. For greater range of regulation present data would seem to indicate the desirability of the rotary converter method on account of limitations in design of the commutator motor imposed by the higher frequencies encountered as the speed of the main motor is reduced.

Incidentally I may say that, in view of the fact that the cost of the synchronous converter method of regulation does not differ greatly from the cost of a standard motor-generator and direct-current motor with shunt field control, I believe there is little if any reason for installing the more complex synchronous converter system of speed control.

This is not the occasion for an extended discussion of the theoretical considerations involved in the design of auxiliary speed-regulating sets and the following brief remarks are for those interested in the practical aspects of the problem of efficient speed control of a-c. motors.

The induction motor may well be considered as a simple static transformer in which the secondary is free to rotate. With the phase-wound rotor blocked and a definite impressed primary frequency and potential, the same frequency, and a potential determined by the ratio of primary to secondary turns, will appear at the slip rings. If the secondary is free to rotate the frequency and potential at the slip rings will approach zero as the speed approaches synchronism. A series of speed-torque and speed-current curves may be plotted for such a motor for each value of secondary resistance. It is therefore like a series direct-current motor in that its speed varies with the load up to synchronism. Its efficiency is approximately proportional to the reduction in speed since the secondary losses are always equal to the ratio of slip to speed times the shaft horse power, or

$$\frac{S}{1-S} \times \text{h.p.} = \text{secondary losses.}$$

If, therefore, we can devise a means of transforming this slip energy at varying voltage and frequency and return it to the system at line frequency and voltage, at the same time automatically substituting the necessary effective resistance in small increments to bring the speed back to the desired value with each change in load, we shall have achieved the required adjustable control at relatively high efficiency.

With the commutator motor method of dynamic control the main motor is started and accelerated in the usual manner with automatic current limit. Upon reaching some predetermined speed the commutator motor is automatically substituted for the accelerating resistance. The commutator motor, which forms one unit of a two-unit motor-generator, is excited from the slip rings of the main motor and because of its series speed characteristic drives the second unit, which is a standard squirrel cage induction motor, slightly above synchronism, causing it to operate as an induction generator and return to the system to which it is connected the slip energy of the main motor less the losses in the motor-generator.

Perfect speed control is obtained for the main motor by manipulating a small three-phase rheostat in the exciting circuit of the commutator motor. Strengthening this field reduces the speed of the main motor, and conversely.

It may assist in getting a clearer physical conception of the manner in which this is accomplished to recall the speed-torque characteristics of the induction motor. When running under given conditions of load and secondary resistance the speed and slip ring voltage are fixed. Conversely, if the slip ring voltage is constant and the effective resistance varied inversely as the load, the speed will remain constant.

It is evident that any sudden decrease in the load on the main motor, for example, produces an instantaneous tendency for the motor to accelerate to some speed corresponding to a lower slip ring voltage required to force just sufficient current through the secondary circuits to produce the new torque values and reestablish an equilibrium of electrical and mechanical forces.

At the instant the load falls off, however, the excess slip ring voltage corresponding to the speed at that moment, maintains in the commutator motor a counter e.m.f. which is equivalent to an instantaneous corresponding increase in the effective resistance in the secondary circuit of the main motor. This increase in effective resistance automatically reduces the secondary current to a new value corresponding to the new conditions of reduced load, while maintaining the same voltage at the slip rings and consequently the same speed, independent of variation in load.

With the synchronous converter method the slip energy of the main motor is first transformed to continuous current which is supplied to a separately excited d-c. motor which in turn drives an induction motor-generator. Speed control is obtained by varying the field of the d-c. motor. The operation is practically as described above, except that an additional unit and electrical transformation is required.

INDUCTION MOTOR CHARACTERISTIC CURVES

A. E. Averrett: The normal induction motor is essentially a constant-speed machine with shunt d-c. load and speed characteristics, but by modifications it can be made to approximate a series d-c. motor by using a high-resistance rotor, or a limited adjustable-speed characteristic by changeable pole connections—this latter includes the cascade connections of one or more motors.

The general qualities of the constant-speed induction motor are quite well known and are shown in Fig. 33; the starting and unstable portion of the curve is shown in dash lines, the stable and working range in full lines.

The efficiency and power factor curve is plotted to torque instead of the usual horse power abscissa so the length of the diagram expressed in torque will be constant, as it is well known that the maximum torque of an induction motor at a given voltage is constant and independent of the secondary resistance, the effect of a change in this resistance merely changing the position at which the maximum torque occurs; it is also well known that within the limits of saturation the torque is proportional to the square of the voltage.

The effect of increased secondary resistance on the efficiency at reduced speeds is readily seen; for instance, at a torque of 2.4 the slip is 2 per cent, the efficiency 92; at the same torque with a slip of 4 per cent the efficiency is 90; similarly if 20 per cent slip is required it will become 74 per cent, since the torque is constant and the speed reduced, the horse power output is reduced proportional to the speed, the power factor and current remaining constant.

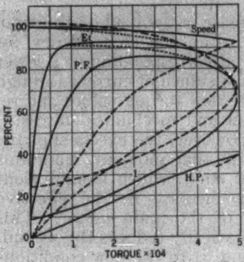


FIG. 33

Fig. 34 shows starting and accelerating curves of the same motor with a variable-resistance secondary which may be either a phase wound with external resistance or different squirrel cages of fixed, moderate, or high resistance.

This curve shows more clearly the effect of resistance in the secondary on starting torque and current.

The standstill position has a slip of 100 per cent, above 100 per cent the rotation is negative although the slip is positive and corresponds to a frequency changer consuming power, and

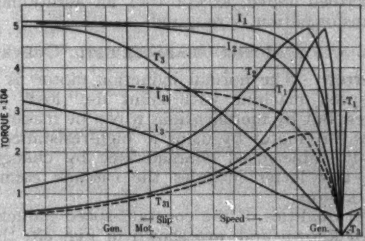


FIG. 34

therefore can be used for magnetic braking by reversing the primary lines. At a negative slip and a super-synchronous speed the torque becomes negative and therefore instead of a motor we have an induction generator returning power to the line; at normal frequency the torque curves above synchronous speed are approximately symmetrical with those below synchronism and therefore the power output as a generator is greater than as a motor. This property is especially valuable in hoisting work to limit the hoist falling speed and return power to the line.

Zero slip is the critical point in regard to torque; at 100 per cent the motor rotation stops, but the torque continues positive and it is very convenient for investigation to continue the curves for large values of resistance and slip beyond the standstill point.

The torque curves for various values of resistance are symmetrical but shifted to the left directly proportional to the total values; for instance on torque curve 1 the maximum torque occurs at 7½ per cent slip. Assume full load at 2.4 the slip is 2 per cent; at 35 per cent slip on the accelerating side we have just enough torque to overcome full load, showing that with minimum resistance the load could not be started.

By doubling the secondary resistance the slip at the same torque becomes 4 per cent, the maximum torque the same, but at 15 per cent slip the full load point for acceleration 70 per cent and the starting torque twice as large.

Since the maximum torque is produced by a certain current the position of the current curve for maximum torque follows the maximum torque point; it is to be observed that both maximum torque and current in curve 3 are on the frequency generator side of the torque curve, that is, beyond 100 per cent slip.

The same class of curves can be used for showing the effect of varying potential as used for starting squirrel cage rotors; the dash curves of torque and current corresponding to a 70.7 per cent compensator voltage tap applied to curve 2, the starting torque being 50 per cent and starting current 70.7 per cent, that is, the starting kv-a. on the line and motor being equal, allowing for no compensator losses.

Multi-speed motors of the changeable pole type have similar torque, speed, and efficiency curves for each set of poles.

Roughly it may be said that resistance control of speed gives a series characteristic with constant power factor and efficiency proportional to speed.

Changeable pole or concatenated motors, on the other hand, give approximately constant speed and efficiency with power factor proportional to the speed. Owing to complications in connections and the initial high cost this latter type is rather limited in application.

The great majority of induction motors used in this country are of the squirrel cage type and where starting conditions are suitable they are almost ideal, but if much more than full load torque is required at starting the loss in running efficiency is objectionable, unless an excessive starting current is permissible. For some classes of intermittent service it is practical to use squirrel cage motors which will start with the maximum torque, but since all the losses are within the motor the heating limit is soon reached.

Under operating features, the following points are of interest. Within the limits of saturation the output and torque are proportional to the voltage squared; this will usually hold for 15 or 20 per cent over or below normal voltage.

The maximum torque at constant voltage is, roughly, inversely proportional to the frequency, provided the ratio of resistance to reactance of the motor is small.

The effect of wave shape is usually slight; the principal effect of wave distortion is to increase the running light current and slightly reduce the power factor.

The effect of unbalancing either phase, voltages, or angles is to increase the heating and decrease the maximum output or torque; this effect is very important, as a 15 per cent unbalancing on a good motor may nearly double the heating.

Single-phase operation of a polyphase motor will cause the motor to fail to start and produce dangerous temperature in the current-carrying phase; if the single-phase operation occurs during running conditions the motor may burn out due to excessive load or break down. The maximum output of a polyphase motor when operating on single phase is slightly less than half.

Small motors may be thrown directly on the line, but where large motors are treated in this manner there are apt to be serious surges on the line and unless the motor windings are extremely well braced there is apt to be injury to the insulation, due to crushing force of the magnetic reactions.

BEARINGS

Lee F. Adams: Bearings may be divided into two general classes, journal and thrust, depending upon the direction in which the load acts. In the journal bearing the load acts at right angles to the axis; in thrust bearings, parallel to the axis. The bearing surface of all journal bearings is necessarily circular in cross-section, while for thrust bearings it is ordinarily flat.

Bearings are also divided into two classes by the kind of contact between the surfaces; that is, bearings having sliding contact, or ordinary bearings, and bearings having rolling contact, or ball and roller bearings.

The detail design of the bearing is very important. Provision must be made for anchoring the bearing metal and for adjustment to compensate for wear. Means must be provided to permit of adjustment so as to insure alignment. Both the bearing and journal must be strong enough to resist rupture under the heaviest load, and also must be stiff enough to prevent undue deflection. The space between the rubbing surfaces is important.

Chief among the materials which are used in the construction of bearings are: Cast iron, steel, gun metal, phosphor bronze, white alloys, aluminum alloys, lignum-vitae, and other hard woods. A good bearing metal must meet the following requirements: It must have strength enough to sustain its load; it must not heat rapidly; it must be easily worked; it must show a small coefficient of friction; it must have long life with small loss of metal due to wear; and in general, it will usually be dissimilar to the metal of the journal with which it is to run. This is broadly true except for hardened steel in contact with hardened steel, and cast iron in contact with cast iron. It is claimed that wear is more rapid and friction greater when the journal and its bearings are made from the same metal.

The ordinary combinations of metals used for motor shafts and their bearings are as follows:

Hard steel journals in contact with hard steel bearings, used for high speeds and moderate pressures. It calls for expert workmanship, as both journal and bearing must be accurately ground and carefully aligned, and under these conditions the service is good.

Hard steel journals with bronze bearings. This is a good combination.

Hard steel journals with cast iron bearings. The cast iron takes on a glazed surface that makes a splendid wearing surface. It is an excellent bearing metal when properly lubricated. Sometimes the bearing surface is sherardized.

In general, hard steel is useful as it may be highly polished without becoming charged with the polishing powder. The polish is very desirable for a bearing surface while the powder remaining in the pores of the metal would soon cause destruction of the containing portion of the bearing.

Soft steel journals with bronze bearings. This is a very common combination.

Soft steel journals with babbitt bearings. This combination is the one most commonly used.

Soft steel journals with cast iron bearings. This combination is used in medium and light weight horizontal motors where the bearing pressures are small and the speeds low, and is also used for step bearings on vertical motors. As stated above, it is an excellent bearing metal when properly polished and well lubricated. Sherardizing is sometimes employed.

Soft steel journals with aluminum alloy bearings. There seems to be a certain range within which this bearing is well adapted and gives excellent service.

Soft steel journals with lignum-vitae and other wood bearings. This combination is used for guide bearings in vertical motors.

Cast iron with cast iron. This combination is a great exception to the disuse of like metals. It is employed for the step bearings of vertical machines; close-grained castings with highly polished surfaces must be used.

The great majority of motors use babbitt bearings. The white metal alloys are solid materials, composed of two or more items, such as aluminum, zinc, nickel, tin, lead, copper, antimony and bismuth in varying quantities and fluxed and alloyed in various ways. Originally babbitt metal had one fixed composition, being made up of 90 per cent of tin and 10 per cent of copper and antimony, the last to make it expand when it cools and fill the mold; but at the present time the term babbitt metal signifies no definite composition, for there are babbitts made up according to three hundred different formulas on the market. Except for a few cases, but two babbitts, one a lead base alloy, the other a tin base alloy, each being the best that can be made, are required for a complete line of bearings, ranging in weight from a few ounces to several tons.

Lead base babbitt is softer than tin base babbitt, as a general rule, and is cheaper because lead costs from one-quarter to one-fifth as much per pound as tin. It is readily appreciated that babbitt can cost anywhere from the price of lead to the price of tin, depending on the proportions used. However, the cheapest kind of bearing metal which when properly lubricated will give efficient service, is equally desirable, compared with the expensive metal which gives no better service. A successful bearing is attained only when the metals are melted slowly, thoroughly, without overheating, kept at a constant temperature while working, and poured properly at the correct temperature. Pyrometers should be used to control the temperature.

However, other things than an unsuitable babbitt metal may cause bearing troubles. Failure of lubrication, an unsuitable lubricant for the pressure and speed conditions, or looseness of babbitt in the bearing shell will cause trouble.

All lubricants fall into three classes: oils, greases and solids. The oils are again divided into three divisions as regards origin: vegetable, animal and mineral.

Vegetable oils commonly employed are linseed, cotton seed, rape and castor. These oils decompose at comparatively low temperatures and are used chiefly for compounding with mineral oils.

Animal oils or fats ordinarily employed are tallow, neat's foot, lard, sperm, wool grease and fish oil. Like vegetable oils, they decompose at comparatively low temperatures and are used chiefly for compounding with mineral oils.

Mineral oils are all petroleum products, and form the whole, or the greater part, of most of the lubricants employed.

Compounds of oils and fats containing sufficient soap to form a more or less solid mass at ordinary temperatures, are called greases. For very high pressures the solid lubricants are sometimes added to the grease.

Solid lubricants used are dry graphite, talc and mica. They are employed only for low-speed work where the bearing surface is restricted in area and the load to be carried is very large. Metaline is a solid compound, usually containing graphite, made in the form of small cylinders which are fitted permanently into holes drilled in the surface of the bearing. Bearings thus fitted will run without any other lubrication. Water has also been used as a lubricant. Disintegrated graphite in oil or water has been used with success.

The generally accepted qualifications of a good lubricant follow:

First. Body (*i.e.*, viscosity) enough to prevent the surfaces to which it is applied from coming in contact with each other.

Second. Freedom from corrosive acid, of either mineral or animal origin.

Third. As fluid as possible, consistent with sufficient body.

Fourth. Low coefficient of friction.

Fifth. High "flash" and burning point.

Sixth. Freedom from all materials liable to produce oxidation or "gumming."

The examinations to be made, to verify the above, are both chemical and mechanical, and can only be made satisfactorily in a laboratory. In the selection of lubricants, the conditions under which they are to be used should first be approximated—*i.e.*, pressure, speed, and in some cases, temperature. It is the practise in many places to use the same oil for all machines, but this is due to failure in appreciating the value of different lubricants rather than economy.

The point of application of the lubricant is of utmost importance, and the method of applying the lubricant to the journal sometimes materially affects the design of the bearing. The most common methods of feeding lubricants to rubbing surfaces in motors are: compression grease cups, wick or siphon feed, oily pad pressed against the journal, oil rings or chains, centrifugal means from an oil well, bath of oil, flooded and forced lubrication.

Ring lubrication is the preferred form for most horizontal motors. The oil reservoirs, dimensions of rings, and oil grooves in the bearings must be carefully designed, as a defect in any one will materially affect the heating. A recent improvement is the substitution of a number of laminations instead of a single oil ring. This decreases the possibility of the oil ring sticking, because with a number of laminations it is not probable that all of them would stick at the same time.

Vertical motor step bearings are generally submerged in oil, and are provided with radial grooves in the journal which allow the oil to be forced over the bearing surface according to its shearing resistance, and at the same time to be circulated through the grooves by centrifugal force, the oil returning to the reservoir. Sometimes the excess oil from the step is taken up through the guide bearings and then returned to the reservoir. If very great pressures have to be carried at high speeds on step bearings, the weight is usually supported on a film of oil or water, maintained by pressure, in which case grooving is not used.

For large horizontal bearings, a foot or more in diameter, flooded oil lubrication is generally used and water circulation is often necessary in addition to the oil lubrication in order to dissipate the heat. Where flooded oil lubrication is used, the bearings are constructed so as to catch all the oil, as it leaves the journal, and pipes carry it to a central receiver. A pump continually circulates the oil to the various bearings, and in the modern installations the oil is filtered and cooled during the circuit. This same process is generally followed when forced circulation is employed. Compression grease cups and wick, or siphon feed lubrication are frequently used on small motors where the bearing pressures are small and the speed low. Waste bearings have been successfully used, at moderate speeds, for small motors for continuous service, and on larger motors for short time service.

Ball and roller bearings have been used in electric motors to a limited extent. In vertical motors they have been used in the step bearings and sometimes in the guide bearings also. In horizontal motors they have had a comparatively limited use, although the trend of public sentiment today is toward ascertaining the relative cost, considering lubrication and upkeep under the severe conditions that motors must meet.

The friction of ball and roller bearings at moderate and high motor speeds is practically the same as the well designed babbitt bearing, on account of the fact that at these speeds the journal runs in a film of oil and not on the metal. It is a well known fact, however, that at low speeds the friction of ball and roller bearings is less than the babbitt bearing. The ball bearing generally used consists of an outer ball race, an inner ball race, and one or two rows of balls. In the production of a high-grade ball bearing, attention must be given to the selection of the steel; to the selection and careful calibration of the balls, their hardness and homogeneity; to the hardening and tempering of the bearing races; and to accurate machine work, close grinding and finishing. The carrying capacity varies with the number and size of the balls. Where ball retainers are used they should be so substantial in construction as to be the last part of the bearing that fails. This is particularly necessary in motor work. These bearings are usually made in various sizes, for a given bore, so as to cover a wide range of loads. Bearings of different manufacture are so arranged as to interchange with bearings of other manufacture when the same series of sequent numbers is compared.

The roller bearing consists of a series of rollers surrounding a shaft or axle and contained in a yoke or cage, for the purpose of holding the rollers in alignment. Inner and outer sleeves or linings are provided, on which the rollers operate. The same requirements for a good ball bearing apply equally to the roller bearing. These bearings are also made in various sizes for a given bore, thereby covering all reasonable conditions of length, load, and general requirements. Both ball and roller bearings are made to carry radial loads and for carrying thrust, either horizontal or vertical.

Both ball and roller bearings must be carefully mounted, otherwise they are liable to make considerable noise. The balls must all be finished to exact dimensions, otherwise one or more balls would take all of the load and probably cause the failure of the bearing. When one ball, or roller, is crushed, it always results in injury to the others, and frequently to the races. It is impossible to supply only one ball, or roller, to the bearing, because on account of the wear on the others, this new ball or roller would take all of the load and result in failure of the bearing. The fact that ball or roller bearings need very little attention, often misleads users to think that no attention whatever is required after the bearing is once installed. Even the most careful mounting of the best ball or roller bearing attainable could not prevent this bearing from suffering severely through lack of proper attention towards maintaining permanently the properties of the lubricant, the exclusion of grit and water, and the cleanliness of the housing. The only requisite for a proper lubricant for ball and roller bearings is a chemically neutral lubricant, free from acid or alkali, and of such consistency that it will circulate freely. Oil is recommended for high-speed horizontal motors, and in most cases for vertical motors; whereas for low-speed motors a good grade of grease is to be preferred. Ball bearings should, however, operate with any density of lubricant.

In the application of ball and roller bearings, a very careful selection must be made, based on the power required, speed of the shaft, size and frequency of overload, and possibility of vibrations and shock.

Step bearings may be ball or roller bearings, forced lubricated or pumped bearing or the collar bearing. The ball bearing may have either grooved or plain plates. The roller bearing may be the straight roller, parallel roller, or taper roller. The collar bearing is used considerably here and abroad. When the collar becomes so large that there is liability of buckling due to unequal heat, it is sometimes divided into segments. Collar bearings are also arranged in series somewhat like the steamship propeller thrust bearings.

MOTOR CHARACTERISTICS

C. A. Adams: I wish to emphasize two points relating to motor characteristics. First, it is often assumed that motors will commutate at any load because the commutating flux is assumed to be proportional to the current; but the curves exhibited this morning by Mr. Lanier show that the saturation of the commutating pole takes place at a much lower current than is ordinarily assumed, chiefly because of the very large magnetic leakage. There is thus a perfectly definite upper limit, a certain percentage of overload, beyond which the machine *will not commutate satisfactorily*, and just as much care should be taken in applying a commutating pole motor to a service which requires excessive overloads for short periods as there is in the case of a non-commutating pole motor. There is a commutation limit in each case, which should be clearly understood as between manufacturer and user.

The second point relates to methods of obtaining several speeds from induction motors by either changing the number of poles or by concatenation. In the first case the motor characteristics are sure to be poor at one speed or the other, usually at all speeds; either the reactance or the exciting current or both being excessive.

In the case of concatenated or cascade-connected induction motors, both the reactance and exciting current double up, *i.e.*, they add together, so that the stalling torque at concatenated speed is about half that of the two motors separately operated. The power factor is also very low. These defects are not usually fully realized by engineers.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 17, 1915, under the auspices of the High-Tension Transmission Committee.

Coypright 1915. By A. I. E. E.

EFFECT OF MOISTURE IN THE EARTH ON TEMPERATURE OF UNDERGROUND CABLES

BY L. E. IMLAY

Abstract of Paper

The author describes a permanent installation which was made for supplying moisture to the earth in the neighborhood of underground cables with the object of reducing their temperature. The approximate temperature of the cables is found by taking with a resistance thermometer the temperature of a duct adjacent to the cable which is the source of heat. In uncovering the conduits and exposing them to air, as a remedy for hot spots in the cable, it was found that the adjacent earth was hot and dry so that it crumbled to powder. This suggested opening a ditch in the ground above the conduit and directing a stream of water through it. This was found to lower the temperature immediately several degrees. Where an open conduit was not practical, water was discharged into a vacant cable duct by means of a hose and this was found to be more effective than the open ditch method.

These experiments led to the installation of a line of porous tile duct in the earth above the conduit, surrounded with clean sand. The leakage of water through the pores of this duct has been found very effective in reducing the temperature of the cables. Whenever the temperature of the cables is found by exploring with a resistance thermometer to approach the danger point, water is turned into the porous drain tile, and the temperature is taken on successive days to see whether the desired reduction has been obtained. In this way one or two men, with resistance thermometers attached to long leads, can keep track of and control the temperature of the cables in a large system. No breakdowns of insulation of cables have occurred due to high temperature since the adoption of this method.

THE PURPOSE of this paper is (1) to describe a convenient method adopted by the Niagara Falls Power Company of determining the temperature of the insulation of underground cables carrying load; (2) to present the results of some field investigations made to determine the temperature of the earth and distribution of heat therein adjacent to underground cables; (3) to show the effect on the temperature of introducing moisture into the earth; and (4) to describe methods that were devised for supplying moisture where needed to reduce the temperature and thereby increase the carrying capacity of cables. The data herewith submitted were taken in the field for a practical purpose; consequently there was no justification for the refinements of laboratory measurements.

(1) It is not practicable to measure directly the temperature of the insulation of a cable at the surface of the conductor, without resorting to apparatus that is not suitable for general use over a cable system. For practical purposes, however, the temperature of the conductor can be obtained by exploring with a resistance thermometer the temperature of a duct adjacent to the cable that is the source of the heat. As we are principally interested in maximum temperatures, a cable should be selected for this purpose that is most unfavorably situated for radiation of heat. This cable can usually be selected by inspection. If the cables are situated as in Fig. 5 and temperatures are taken in duct marked *T*, the temperature of the insulation at the surface of the conductor is taken from a curve that applies to that particular cable. Fig. 1 is the curve for a 3/0, three-conductor, 11,000-volt cable, and Fig. 2 is the curve for 1,250,000-cir. mil, 2200-volt cable. For example, if a 3/0, three-conductor, 11,000-volt cable is carrying 170 amperes and the temperature of the adjacent duct *T* is 39 deg. cent., the temperature of the insulation at the surface of the conductor is 72 deg. cent. These curves are deduced from a formula given by Messrs. Atkinson and Fisher in a paper presented in 1913 and published in Vol. XXXII of the A. I. E. E. TRANSACTIONS, page 325.

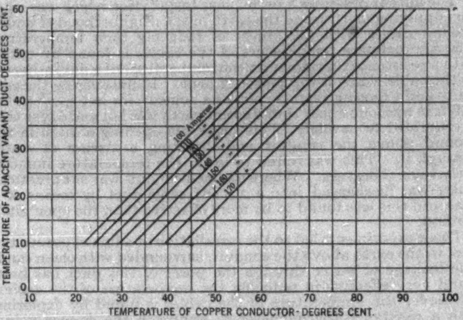


FIG. 1—3/0 THREE-CONDUCTOR 11,000-VOLT PAPER AND LEAD CABLE

The temperature at which paper-insulated lead-sheath cable can be operated safely has been carefully investigated, particularly by Mr. Henry W. Fisher. Some of the results of his investigations are given in the paper above referred to and in Foster's Handbook and the Standard Handbook. The maximum safe limiting temperature of paper insulation at the surface of the conductor in a cable, as stated in the Standardization Rules of the A. I. E. E., is 85 deg. cent. less a number of degrees equal to the kilovolts at which the cable is operated. In the case of a three-conductor, 11,000-volt cable, the limiting temperature of the insulation at the conductor is therefore 74 deg. cent., and in the case of a 2000-volt cable the limiting temperature is 83 deg. cent.

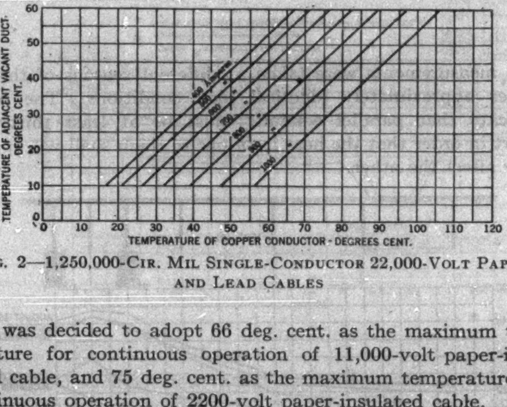


FIG. 2—1,250,000-CIR. MIL SINGLE-CONDUCTOR 22,000-VOLT PAPER AND LEAD CABLES

It was decided to adopt 66 deg. cent. as the maximum temperature for continuous operation of 11,000-volt paper-insulated cable, and 75 deg. cent. as the maximum temperature for continuous operation of 2200-volt paper-insulated cable. This is eight deg. cent. lower than the safe limiting temperature specified in the Standardization Rules, which are based on fluctuating loads with peaks of short duration.

(2) To get some idea of the seasonal variation in the temperature of the earth, readings were taken each month in the year at a point about three ft. below the surface of the earth. This point was chosen near a section of conduit where overheating of cables had occurred, but at such distance that it was practically unaffected by heat from the conduit. In Fig. 3 the lower curve shows the seasonal variation in the

temperature of the earth. The upper curve shows the temperature variation three ft. below the surface of the earth, above a conduit containing cables. Fig. 4 shows the distance to which the earth surrounding a conduit is affected by heat from cables.

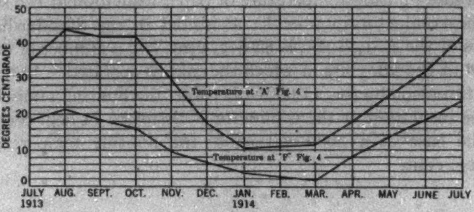


FIG. 3

The measurements were taken at different seasons of the year under approximately identical load conditions. The results indicate that parallel conduits must be at least thirty feet apart in order that the heat from one of them shall not appreciably affect the other.

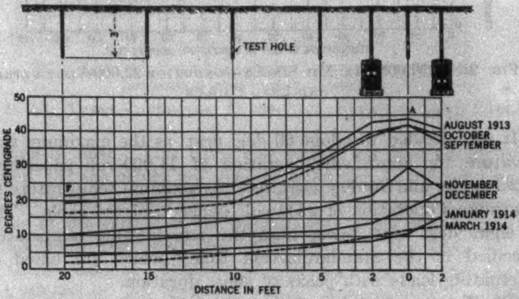


FIG. 4

(3) An effective remedy for hot spots in cables is to unearth the conduit and expose it to the air. In uncovering a conduit directly after a cable breakdown, it was found that the adjacent earth was very hot and so dry that it would crumble to powder. This condition suggested digging a ditch a few inches deep in

the ground just over and along the length of the conduit and directing a stream of water through it, as irrigation for crops is carried on in the Western States. This remedy immediately lowered the temperature of the cables several degrees. Where conduit was under roadways and paved streets the open ditch method was not available, and at these points water was discharged into a vacant duct by means of a garden hose. This was found to be even more effective than the open ditch method. In some cases, however, where multiple duct was used, the water would not flow from one manhole to another, being lost on the way. Fig. 5 shows the effect on the temperature of cables of water discharged in a vacant duct. Two and a quarter gallons per minute reduced the temperature 13 deg. cent. and held it about constant. When the amount of water was increased to twelve gallons per minute, the temperature was reduced 13 deg. cent. further and then became constant. The remainder of the curve shows the gradual rise in temperature after the water was shut off.

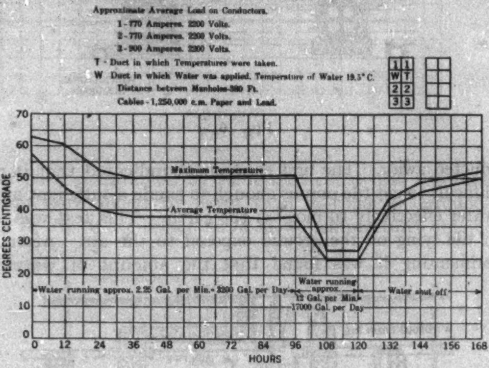


FIG. 5

(4) These crude methods of reducing the temperature pointed the way to a permanent installation to control the temperature of cables in conduits. The method finally adopted is shown in Figs. 6 and 7. Porous drain tiles four inches in diameter were made in sewer pipe molds. These were laid in a trench in the

earth above the conduit, as shown in cross-section in Fig. 6. The joints were cemented to prevent leakage except through the pores of the tiles. This tile serves a purpose exactly opposite to that for which drain tile is generally used; that is, water is supplied through it to the surrounding earth, instead of being conducted away. The first experiment indicated that it might be difficult to get tile porous enough to exude a sufficient amount of water effectively to moisten the earth. This test was made with tile lying on the ground exposed to the air. After some experimenting it was found that the amount of water that would pass through the pores of the tile could be greatly increased by a covering of earth. Clean sand around the tile was more effective in producing the desired result than any other material tried.

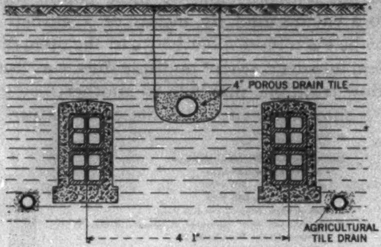

4" POROUS DRAIN TILE
4 1"
AGRICULTURAL TILE DRAIN

FIG. 6

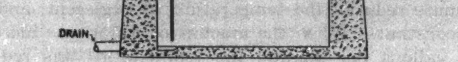

4" POROUS DRAIN TILE
1" GAL. IRON PIPE
1" WATER SUPPLY
1" GAL. IRON PIPE
DRAIN

FIG. 7

In Fig. 8, curve *A* shows the distribution of heat in the earth at right angles to a line of conduit containing 2200-volt cables before water was applied by the drain tile method. Curve *B* shows the temperature after three gallons of water per minute had been applied about thirty-six hours.

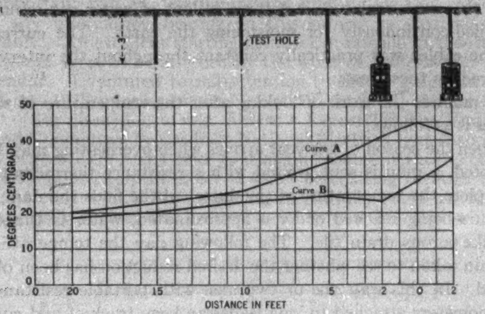


FIG. 8

It has been maintained by some that cables will run cooler in conduit surrounded by earth than in conduit surrounded by air. In Fig. 9 the upper curve shows temperatures obtained in duct indicated by letter *T* before any effort was made to reduce the normal temperature. The middle curve shows temperatures obtained in the same duct after the top of the conduit

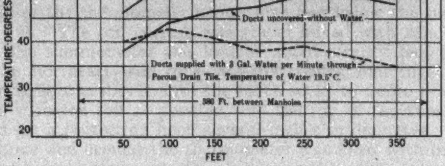


FIG. 9

had been unearthed. In this case the sides of the conduit were still covered with earth. The temperature of the air at the time of this test was about 16 deg. cent. The lower curve shows temperatures that were obtained after the drain tile had been laid, the earth replaced, and three gallons of water per minute supplied continuously for moistening the earth. The current on the cables was practically constant throughout the interval covered by these tests.

In practise the work of looking after the temperature of the cables is as follows:

When the season of the year arrives when overheating may be expected, a man is sent around with a resistance thermometer to explore the temperature of the ducts. If he finds the danger point is being reached or even approximated, water is turned into the porous drain tile. The following day the temperature is again taken to see whether the desired reduction has been obtained. In this way one or two men with portable resistance thermometers attached to long leads can keep track of and control the temperature of cables in a large system. Since this plan was adopted no breakdowns in insulation of cables have occurred due to high temperatures. The plans for installing the porous drain tile for cooling have been adopted as a standard, and whenever new conduits are laid in which high temperatures may be expected, the conduit will be provided with this means of cooling.

DISCUSSION ON "THE EFFECT OF MOISTURE IN THE EARTH ON TEMPERATURE OF UNDERGROUND CABLES" (IMLAY), NEW YORK, FEBRUARY 17, 1915.

Charles W. Davis (by letter): Soil temperature plays such an important part in determining the limiting load on cables, that any information bearing on this subject is particularly desirable. An excellent starting point for discussion of the subject would seem to be afforded by the work of Professor H. H. Callendar. I ventured to call attention to the investigation at the June, 1913, meeting of the National Electric Light Association. (See discussion of Mr. Abbott's Report for The Underground Committee, Proceedings National Electric Light Association, page 673). And I refer to it again because it throws considerable light upon the effect of water percolating through the soil—an effect which Mr. Imlay has so skilfully made use of in a practical way; and also because it points out the errors which may arise in the determination of soil temperatures at various depths.

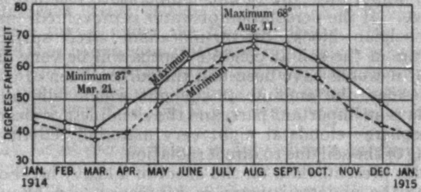


FIG. 1

The curve shown in Fig. 1 is compiled from data taken in Pittsburgh, by a method which I assume is similar to that used by Mr. Imlay.

The thermometer was located in a vertical tube of micarta, the bulb of the thermometer being three feet below the surface of the soil. The soil surface was gravel mixed with sand and clay. The thermometer was located about twenty feet away from the northeast wall of a two-story brick building. The micarta tube was driven into the earth so as to make as close contact with the soil as possible, and the top of the tube was covered by a protecting hood several inches in diameter. The tube above and around the thermometer was filled with cotton to prevent convection currents. I mention these details to show that considerable effort was made to minimize the errors which Callendar refers to as attendant upon this method, on account of water following the contact surface between tube and soil;

and on account of the conduction of heat by the vertical thermometer tube.

The percolating of water downward along the surface of the tube results in unduly low readings after a cold rain or unduly high readings after a warm rain.

I am satisfied that in spite of such precautions as were taken, the readings in the winter months as shown on the chart I present are considerably lower than actually existed in the soil at the same depth, but far enough away to be unaffected by the errors due to percolating water, and conduction of heat upward along the thermometer tube.

It would be interesting to know from Mr. Imlay what precautions if any were taken to prevent a similar error in his determination, the results of which are represented in the lower curve of Fig. 3 of his paper.

The results of Callendar's work, and data at hand from other sources, make it obvious that the surface of the soil plays an extremely important part in the temperature reached beneath the surface. If the percolation of water is prevented—as by an asphalt, belgian block, or tar-macadam street surface—the temperature of the soil at conduit depths will be very different from what it would have been had the surface been of gravel or sand. Besides, the amount of sunlight which falls upon the surface plays an important part, and the cloudiness or clearness of the atmosphere—clouds at night very materially cutting down the cooling of the soil due to direct radiation.

Callendar presents data on the effect of a heavy layer of snow in keeping the undersoil warm in winter; and on the cooling effect of the earth's radiation during clear nights.

Where ducts are located in closely built-up city streets, whose exposure is such that the street surface gets directly, or by reflection from the neighboring buildings, the maximum of sunlight, and where the street surface is of asphalt or of other waterproof material, it is highly probable that the soil temperature at three feet below the surface at the end of December is not much below 50 to 60 deg. fahr., in such cities as New York, Philadelphia and Chicago. This is considerably above the December maximum of 3 deg. cent. (34 deg. fahr.) shown for December by Mr. Imlay's curve, or 42 deg. fahr., shown on the curves I present. To be conservative in the operation of cables in or around the holiday season requires, I believe, a recognition of the fact that these higher minimum soil temperatures may prevail.

It may be worth while noting that Callendar avoided difficulties attending the use of vertical thermometer tubes, by digging a vertical trench, and then inserting the resistance thermometers at the extreme end of a half-inch diameter horizontal hole bored for a distance of three feet into the sidewall of the trench, the trench being carefully filled in afterward.

H. W. Fisher: Mr. Davis's curve is in general form like the curve shown by Mr. Imlay. The maximum temperature of

68 deg. fahr. was on August 11; the minimum temperature of 37 deg. fahr. was on March 21. In these curves there is a difference between the curve of minimum and maximum for each day of six degrees in some cases, showing there were causes for such changes.

W. S. Clark: There is one thing I am quite interested in, and that is in what month of the year the curve given in Fig. 5 was made. It is quite interesting to know whether that is a winter or a summer curve.

The other thing that struck me, without having made any of these measurements—and I do not live as far north as Niagara Falls—is the fact that we have water-pipes freeze solid at a depth of over three feet, which would indicate that we get minimum temperatures at some places of a little below zero. Five above zero is the last point, the lowest point here on this curve Fig. 3, and it seems as if the lowest temperature would go below that in some of the northern cities.

A number of years ago the Chicago Edison Company connected its Harrison Street station to its still older Adams Street station by a tunnel under the Chicago River. The loads increased and they had to have greater carrying capacity right away.

The company had been in the habit of pumping water out of this tunnel, so one engineer said, " Suppose we pump water into the tunnel." This was done, and it was very successful in reducing the temperature.

Some St. Louis records taken in July show a minimum duct temperature of 40 deg. cent., and the maximum of about 45 deg. cent., over a 24-hour run; and on a perfectly clear day of bright hot sunshine. The street was paved with belgian block, and the variation of temperature in 24 hours was very small.

These data point to two things: One is the desirability of having a weatherproof duct—a waterproof duct. With a waterproof duct you can have your soil outside as wet as you please, and get rid of your heat that way without risk of electrolysis; or you can pump water through your ducts and not lose the water.

Now, I do not think any of the multiple-tile ducts could be made waterproof enough to circulate water through them and have it come out at the other end of the line.

The second thing is, when you come to handle large units of power you must push the e.m.f. up to keep your investment in copper and ducts somewhere within reason.

J. P. Wintringham: There is one item perhaps theoretical rather than practical that I think would be of interest to bring into the proceedings at this point; and that is, that at very low temperatures the resistance of pure metals, notably lead and mercury, becomes very small.

At a temperature of about 4 deg. absolute, mercury seems to loose all its resistance, and a thread one millimeter in diameter will carry one thousand amperes without any signs of heating. These experiments of Kamerlingh Onnes will be found in the publications from the Physical Laboratory of the University of Leyden, but they may have been carried on in Pittsburgh.

Philip Torchio: From the standpoint of the subject of this paper high-tension cables have greater limitations on account of the losses in the dielectric being considerably higher than in lower voltage cables. It must not be forgotten in considering a cable system that the temperature due to losses in dielectric is relatively of secondary importance with low-tension cables. I mean such cables operating up to, say, 2200 volts.

As Mr. Fisher has called attention, the Underground Committee of the National Electric Light Association has given considerable thought to the same subject. One of the member companies reported that, on account of heating of cables in ducts, they had to reduce the load in summer to one-half the safe carrying capacity of the cable in winter time. For that reason, instead of building subways with a great number of ducts bunched together, they are trying to build the new extensions in vertical lines of ducts, with intervening space of earth, so that each duct is on two sides surrounded with earth.

In the former instance the lack of dissipation of heat was due to the drying-up of the surrounding earth, which became a heat insulator around the bank of ducts.

The possibility of using water from the street seems impracticable to me. The plan of pumping water through the ducts, as suggested by Mr. Clark, may have some merit.

C. A. Adams: The information contained in this paper is very valuable, but still somewhat empirical. If we knew the thermal conductivity and the specific heat of various kinds of soil with various degrees of moisture, it would be possible to compute the temperature of an underground conductor under any specified conditions with a fair degree of accuracy, even including the time element. If the results of tests such as here recorded could be reduced to such fundamental terms, it would vastly extend their range of usefulness.

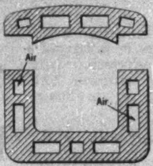
W. S. Franklin: I think it would be well to determine the thermal conductivity of the soil under different conditions. Something along this line was done thirty-five or forty years ago as a preliminary to the calculations by Lord Kelvin of the rate of cooling of the earth; and no doubt one could get some important data by looking back to this early work of Lord Kelvin.

In any actual measurements the difficulty is to know the varying moisture content of the ground. The United States Department of Agriculture has developed a satisfactory method for following the variation of moisture in the soil without disturbing the soil, by placing in the soil at a fixed distance apart two small electrodes and determining the electric conductivity of the soil. The results so obtained are interpreted as moisture content on the basis of empirical tables previously determined.

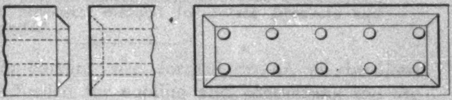
P. W. Sothman: In connection with this subject, I think we should have another line of investigation carried through with conduits that are entirely porous as compared with conduits that are either glazed or unglazed.

In European countries, underground systems are invariably installed with non-glazed conduits made of concrete or cement. One of the great claims put forward in favor of unglazed conduits is good radiation of heat from cement conduits. In some types of conduits, air-spaces are provided in the walls as illustrated in the accompanying sketch.

It has been found that the heat radiation from these unglazed tiles or conduits is much greater than for the glazed types. From this point of view, it would be very interesting to compare Mr. Imlay's investigation with the results obtained abroad.



VERY POROUS
TILE CONDUIT



VERY POROUS CEMENT DUCT

George N. Lemmon: In connection with the conductivity of heat and its dissipation through the earth, a rather interesting thing occurred in Youngstown, Ohio, several years ago.

At one of the old stations the negative return from the rail, left the rail in the street and went through the car-barn floor to the switchboard in the power house. The floor of the car-barn was earth with some ashes mixed with it. In the course of years it had become extremely dry—there was not even moisture from washing the cars. The circuit was interrupted one night due to a fusing of the cable in the car-barn floor. This was due to the dryness, for out under the sidewalk where the earth was moist there was no trouble.

It was a decided example of the difference in heat conductivity between dry soil and soil slightly moistened.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 17, 1915, under the auspices of the High-Tension Transmission Committee

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OIL CIRCUIT BREAKERS

NOTES ON ARC PHENOMENA AND TENDENCIES IN DESIGN

BY K. C. RANDALL

ABSTRACT OF PAPER

The purpose of the paper is to present a brief explanatory discussion of some of the arc phenomena in oil circuit breakers and to describe the present tendencies in oil breaker construction and practise. A proposed method for rating breakers and specifying is included.

IN AN alternating-current arc formed in an oil breaker, opportunity is afforded for cooling and condensing the arc gases as the current passes through zero, and if these are completely condensed or removed and replaced by sufficient oil distance, the current will not be reestablished, because the medium intervening between the separating contacts has been changed to an insulator of sufficient dielectric strength to withstand the potential tending to reestablish the current. If the separation of contacts is not sufficient, or if the condensation and removal of gases is not adequate, or if the arc contained volatilized metal from the contacts, of sufficient quantity, the current will be reestablished. With an ideal oil breaker the current will not continue after the first zero value following the first complete separation of contacts.

In actual practise, on large powers, possibly few breakers comply with this ideal, because the current continues beyond the first zero value, due to (1) insufficient separation of the contacts; (2) large amount of gas formed in the arc; (3) reduction of insulating value of oil between contacts owing to suspended metal and carbon particles condensed after each successive half-cycle arc. If the particular breaker application is too far from the ideal the reestablishment of current after the first and subsequent zero values will continue indefinitely, or at least be repeated so many times that the breaker will be damaged or destroyed. Usually, in such instances, it is a case of misapplication or failure to maintain initial conditions, for every breaker has its limitations within which it is good, but there may be a wide difference in rupturing capacity of breakers of given cost and space requirements, and it is by these differences that the better breakers are distinguished. Increase in capacity of a system, failure to maintain breakers either as to mechanism or insulation, change of current limitations, changes in methods of operation, faulty relays, etc., all may act to increase the duty on a breaker, even to destruction.

Plainly, it will be very difficult to interrupt an alternating current abruptly during any half cycle, for the same reason that an abrupt rupturing of a field current of a generator is difficult or dangerous. So it is that the endeavor of the breaker is focused upon providing against the reestablishment of current after normal zero value. Clearly, each time the current is reestablished and continues to the next zero value, energy is dissipated in the breaker tank, due to the arc. The oftener this is repeated the more the contacts are burned, the more the oil deteriorates, and the less the chance is of finally interrupting the current.

Assume a breaker, operating on a 15-cycle circuit of a gives current and voltage, begins separation of contacts just as the current is normally passing through zero, and that the separation of contacts (acceleration) is such that the current ceases at the next zero. This same breaker operated in the same way on a like 60-cycle circuit will dissipate the same energy, if the current is of like volume and continues for the same time; that is, ceases at the fourth zero point. But, had the breaker been accelerated to prevent re-establishment of the current after the first half (60 cycles), the minimum energy could have been dissipated. Similarly, on 30 cycles, the speed of opening should have been twice that for 15 cycles; and in general, the rate of contact separation should be proportional to the frequency of the system when endeavoring to attain the ideal condition of terminating current at the end of the first half cycle.

The extinguishment of the arc will be near the normal zero point regardless of the speed of opening, because, whatever the rate of separating the contacts may be, tending to rapidly insert a dielectric in the form of cold oil, a potential tending to maintain the circuit current will be developed, and this, in general will be adequate to break down the intervening dielectric. Thus the current will be sustained until practically its normal zero point is reached. This will be true even if the whole breaker travel were accomplished in, say, ⅛ or ⅓ cycle; the current would still continue to practically the normal zero point, as each higher rate of current reduction gives a correspondingly higher sustaining voltage for maintaining it.

Furthermore, neglecting the voltage peaks required for reestablishing the current, the maximum steady voltage attainable across an arc is limited, regardless of the length of arc or current volume, and hence, the same loss is developed regardless of the rate or length of opening, provided the current and time of arcing is the same. This is explained as follows: With practically any current encountered in serious breaker problems, the ionization in the arc space will be quite complete and, therefore, it will constitute an excellent conductor, becoming better as it is further heated by increased currents, so that the drop will remain practically constant independent of the current volume provided it does not fall sufficiently to threaten deionization. The distance between contacts when the arc space is completely ionized has very little effect on the drop across it, provided the currents remain large as in ordinary breaker practise. This, therefore, demands for the best breaker results, that the speed and length of opening be such that current may never be established after the first zero value of current following the separation of the breaker contacts.

From the preceding, it is plain that on low frequencies an arc enduring to the first zero value following the separation of contacts will, on the average, continue for a longer period, and therefore dissipate more energy than an arc of like current but of higher frequencies, also extinguished at the first succeeding zero value. Therefore, in general, the high-frequency currents will be interrupted with the smaller demonstration and lesser breaker duty than similar lower frequency currents, and the energy dissipated will be, on the average, for an ideal breaker, about inversely proportional to the frequency.

After fixing the proper design of conducting details, allowing liberally for the continuous current-carrying capacity and for insulating distances—dielectric strength, such that liberal tests are successfully withstood—the problem of rupturing capacity still remains. On the higher potentials the insulation problems largely govern the dimensions. On the lower potentials mechanical considerations may largely dominate.

Oil, being the accepted insulating medium, convenient because of its dielectric value and liquid form so well suited to cooling and replacing arc gases, should, particularly on higher potentials, be of high grade. At the lower potentials the dielectric value of the oil is not so important. Some designs have been devised with the purpose of improving the circulation or agitation of the oil when the breaker operated so as to introduce fresh cool oil between the contacts thus sweeping away and condensing the arc products, and interposing a new clean dielectric which will not be punctured by the available potential tending to reestablish the current. Oils of low volatilization, slow carbonization and fair insulating value are desirable for average applications. For very low temperatures non-freezing oil should be used*, but these are usually so volatile at ordinary summer temperature that another oil must be used. A large oil volume is considered favorably, as through it the shock from the largely explosive action of enormous arc currents is reduced and absorbed. A large volume of oil will keep clean longer in a given service, and therefore maintain its insulation value better, besides initially affording better insulation distance. A large head of oil over the contacts means a heavier pressure on the arc bubble with consequent increased tendency to confine and quickly replace it with fresh oil. Facility of ionization of arc gases is decreased by higher vapor pressure, thus making reestablishment of the arc more difficult. The reduced volume of the gas bubble, due to the increased oil head, also disturbs the main oil body less, a very important matter when near the limit of rupturing capacity, especially of single-tank units.

The length of break is all-important, but if consideration of arc gases could be entirely eliminated, the length of break should only be sufficient to interpose an oil distance which would not be punctured by the available potential. As a rule, this would require but from 1 to 10 per cent of the actual travel available, as it takes 50,000 volts to puncture ¼ in. of moderately good oil. Therefore, the travel represents a very large margin over that indicated as necessary by the dielectric value of the oil alone; but it is necessary due to the reduced dielectric strength—in fact, conducting condition—prevailing during the arcing period. In a number of tests on a 25-cycle power circuit at 12,000 volts, about 15,000 amperes were interrupted at the end of a 4-in. travel (one-half cycle), although the contacts finally separated 9 inches.

An increased number of breaks in series, entirely neglecting method of accomplishment, would seem desirable, as the simultaneous opening of several breaks will accomplish the intervention of a given oil distance more rapidly than will a smaller number of breaks, assuming that the rate of contact separation remains roughly the same for both. With the increased oil distance, recovery after the first zero point is less likely. On the other hand, it is apparent that with the drop across each arc practically constant, the energy dissipated in the multi-break unit during the first half-cycle will be roughlv proportional to the number of breaks and greater than the fewer breaks. It probably will be considered better to tolerate this condition, with the assurance that the current will never pass the first zero, rather than contend with a design wherein the rate of breaking is not adequate to prevent repeated reestablishment of current after successive zeros. The deteriorated condition of the oil is considered more serious with a slow-operating breaker after passing several zero values, because of the longer arcing time, than with the design dissipating the same amount of energy, but previous to the first zero value. A scheme to increase the arc voltage would not be welcome, but a plan to reduce it, and yet retain conditions opposed to current recovery after the first normal zero value, is desirable, as in this way the total energy dissipated would be reduced. Whether a multi-break design is to be preferred over the usual break will be

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*Most oils are unsatisfactory below 0 deg. or −10 deg. fahr

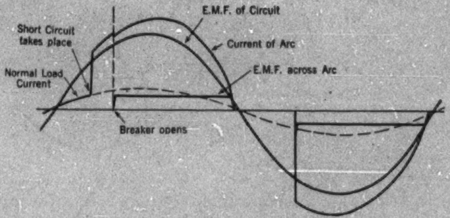


FIG. 1—VOLTAGE AND CURRENT CURVES FOR AN OIL CIRCUIT BREAKER ARC IN A NON-INDUCTIVE CIRCUIT

The normal voltage and current of the non-inductive circuit are shown; also the sudden increase of the alternating current occurring at the moment of short circuit. Coincident with the breaker opening, a slight diminution in current volume is noted, resulting from the increased circuit resistance, due to breaker arc. The voltage across the arc is shown as a low practically constant value, developing at about the moment of opening and continuing until near the zero value when it becomes the circuit voltage, owing to the cessation of current. It continues along this curve until it has reached a value sufficient to puncture the dielectric between contacts, and thus reestablish the arc, when it again drops to the low practically constant value, shown in the first half cycle. The current follows practically the sine wave form until near the first zero, when, owing to reduced volume and consequent lowered heating, the arc gases are chilled and deionized, suddenly interrupting the current slightly in advance of the normal zero point. From here the current remains zero until suddenly reestablished in the opposite direction by the normal circuit voltage. This same cycle will be repeated until the contact separation becomes sufficient to prohibit reestablishment of current by the available circuit voltage.

decided by what may be accomplished by the common two-break construction, when highly accelerated. It is plain that the additional mechanical complications and consequent larger masses of the multi-gap breaker that must be moved, will constitute a very serious problem.

Consideration of Fig. 2 makes apparent the general effect of self-induction on current interruption. On a non-inductive circuit (the current and voltage in phase) the chance of current reestablishment is much less probable than with an inductive circuit wherein—with lagging current—voltage is available for reestablishing the arc as the current emerges from the zero value. For this reason interruption of the current at the higher frequencies will be more difficult as the current lag for any given circuit is greater and the voltage tending to reestablish progresssively more as the frequency is increased. On the other hand, the total self-induction of high-frequency circuits will usually be less

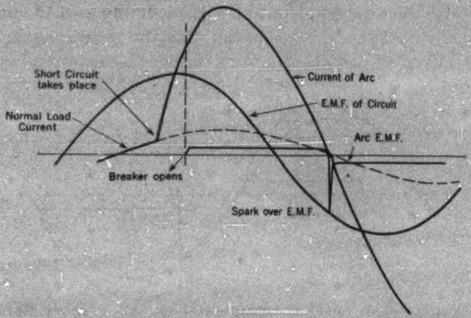


FIG. 2—VOLTAGE AND CURRENT CURVES FOR AN OIL BREAKER ARC IN AN INDUCTIVE CIRCUIT

The normal voltage and current in an inductive circuit are indicated and the development of the alternating current from the moment of short circuit with its decrease to zero and its later recovery in the opposite direction is shown. The voltage across the arc is also shown from the moment of breaker opening to near the normal current zero point where a high peak is developed which immediately drops to a low practically constant value, as shown in the first half cycle. Fig. 2 contrasts with Fig. 1 in that the current at the time of short circuit is established gradually, and passes through zero to a negative value, practically as a sine wave, this action being repeated at each zero point until finally at the last zero recovery is impossible. From the moment of the breaker opening the arc voltage develops almost immediately to a steady small value which holds until just before the first current zero. Here the current value has been so reduced that the lower rate of energy dissipation is no longer able to prevent chilling and deionization of the arc gases. Thus, the arc gases change suddenly from the nature of a conductor to the nature of a dielectric and tend to terminate the current with equal suddenness slightly previous to the normal zero point. This action is acknowledged through the self induction of the circuit by a sharp voltage peak which breaks down the dielectric and is following by reionization within the arc space, whereupon the low arc voltage, as shown in the first half cycle, again appears. This same potential peak will occur at each successive zero until the current is finally terminated, when the arc voltage becomes the circuit voltage.

than on circuits of lower frequencies, and, therefore, the termination of the arc current will be facilitated. This is apparent, for in the endeavor to suddenly rupture the current, but little sustaining power is encountered in the practically non-inductive circuit, while in the highly inductive circuit every change in current is accompanied by a corresponding potential tending to maintain that current.

In the breaker arc, as chilling occurs near the zero value of current, the ionization of the gases ceases and conductivity in the arc space is so reduced that the current can only be established by a potential capable of puncturing the resulting dielectric which has become very much stronger than it was previous to deionization. Very high arc currents, with their correspondingly high temperatures and increased volume of arc gases, make deionization much more difficult, thus rendering the successive reestablishment of current much easier. The enormous energy dissipated by very large currents as the contacts first separate is a demonstration of an explosive character. Breaker tanks have been blown off with practically no contact burning, evidencing a violent pressure of short duration. So it is that larger currents are more difficult of interruption.

Facility of deionization of the arc gases will depend upon the temperature and pressure of the surrounding oil, and the shape and volume of the contacts, and also on their heat conductivity and vaporizing temperature. Plainly, contacts of small volume with sharp edges, low heat conductivity and low vaporizing temperature are least favorable to the breaker. From this it is apparent that a small breaker, on the score of volume and shape of contacts alone, is more severely tried than a larger unit. This plainly emphasizes the desirability of large contacts of smooth shape.

Gravity-actuated breakers never open quite as rapidly as a free falling body, and sometimes the retarding influence of the mechanism is very serious, so that accelerating devices are now common, and the rate of opening is in many breakers much more rapid than that obtainable from unimpeded gravity alone. The matter of stopping the moving parts as they approach the end of the stroke has to be carefully considered, in the case of larger breakers, even when unaccelerated, but when highly accelerated the problem is more serious and may even be complicated. Fast closing is important, like fast opening. An explosive action is likely as the arcing tips of a slow-closing breaker touch when closing against a short circuit, due to the violent energy dissipation and consequent volatilization of contacts and oil. This action is identical with that occurring in a slow-opening unit. Modern practise, particularly on the score of general simplicity, favors the solenoid operation for all remote-controlled oil breakers save when manually operated.

Tending to limit the maximum capacity that may be ruptured by a single plain breaker, large current volumes are the most serious problem because of their practically explosive action. As the operating voltage increases, the available currents decrease proportionately, but the difficulty of the problem is not much improved until rather high potentials are reached, when the distances necessary for obtaining a proper margin of safety for insulation and test afford relief from mechanical shock encountered in the designs for lower voltages. Probably the maximum power that plain breakers as now built could rupture will approx-

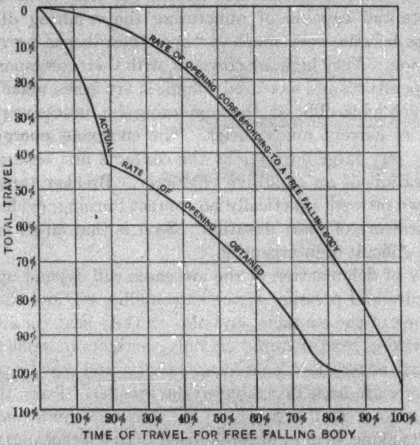
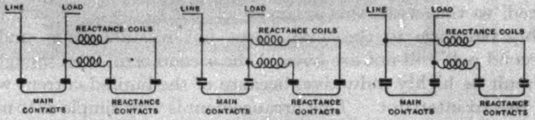


FIG. 3

This figure shows the curve of a free falling body, which is the best that a plain unaccelerated breaker can do. It also shows the actual rate of opening of a specially accelerated breaker built for extra high voltage service. The unusual acceleration in the first 40 per cent of the travel is obtained by a retrieving contact which is drawn out by the already highly accelerated main contacts and then suddenly retrieves while the main contacts continue to near the end of the stroke, where they are retarded and the blow from their fall absorbed.

imate the power that would be delivered through a shunt-tripped breaker at the time of opening, by 150,000 kv-a. of modern high-reactance generators on a single bus, feeding a maximum short circuit, so that the current is limited only by the generator impedance. In general it will be easier to handle the given short circuit at, say, 15,000 volts, because at higher potentials the chance of reestablishment may be greater, while at lower potentials the volume of current would seriously increase the total amount of energy to be dissipated in the arc, and therefore the difficulty of terminating the current. A breaker adapted to such a station for 15,000-volt service is illustrated in Fig. 6, and is constructed with particular regard to obtaining the strong tank and supporting details, so that even with violent energy dissipation in the arc, the mechanical details will withstand the shock. This breaker will require for installation a space approximately 7 ft. 4 in. by 2 ft. 1 in. by 9 ft. high.



A—BREAKER CLOSED

B—FIRST STEP—
MAIN CONTACTS OPEN,
REACTANCE CONTACTS CLOSED

C—FINAL STEP—
ALL CONTACTS OPEN,
LINE CLEAR

FIG. 5—TERMINAL AND CONTACT ARRANGEMENT WITH REACTANCE COILS OF HIGH-VOLTAGE REACTANCE BREAKER

Sequence of operation of breaker shown in Fig. 4.

In endeavoring to raise the limit of power to which plain breakers may be applied, without employing permanent current-limiting reactance, originally the resistance and later the reactance breakers were developed. Initially, as is fairly well known, the design took the form of a resistance with a number of contacts, each one introducing more resistance into the circuit, and the last opening the circuit. This was later simplified, making but two steps, the first introducing a considerable resistance, and the second opening the circuit. Because of difficulties in the design and application of resistance, reactance was substituted, and a considerable number of such breakers has been built. The reactance breaker followed the form of the later resistance breakers in that two steps were employed; one to introduce the current-limiting reactance, and the second to open the circuit. The reactors are designed to carry current but a very short period, as the time between introducing them into the circuit and final rupturing of current is very short—considerably less than one second. In this way a small conductor of many turns affords in small space a very considerable reactance. A still later development of the reactance breaker idea has somewhat simplified the matter. Instead of employing interlocked mechanism, such that the first mechanism introduces the reactors, and the second opens the circuit, two similar breaks are now employed operating simultaneously from a common mechanism—one of which is shunted by a reactance coil. It is well known that the shunted arc is inclined to be unstable, and in actual test it has been found that the shunted breaker does its duty promptly and with very little effort. The final break, of course, will only involve the current permitted by the limiting reactance. This will be easily terminaated, so that with this arrangement the shunted pole will probably only arc to the first zero—not reestablishing—and the second pole will not arc beyond the second zero, even though the circuit be highly inductive, because of the limited current which it has to interrupt. This arrangement is very simple as to mechanism, permits the employment of the standard breakers and allows mounting the current-limiting reactors wherever it may be convenient in the installation.

For some time breakers were supplied according to the judgment of the designer of the equipment, or according to the ideas of the purchaser. No definite plan of rating or determining capacity existed. Later, more attention was paid, especially to installations on the large powers, and some approximations were made, as to what the proper rating for the breaker should be. Now, installations are quite generally receiving individual consideration in the breaker applications, and the desirability of a uniform method of rating is growing constantly more pressing. A method, developed from experience, tests, and consideration of common problems, assumes the breaker to be installed directly on the bus and to protect same against nearby short circuits. In determining the maximum breaker duty a generator equipment of 8 per cent impedance, capable of delivering 12½ times normal current at the first instant of short circuit, is assumed. It is also assumed that by the time breaker opening occurs, this maximum current value will have decreased to one-half the initial, namely, to 6¼ times normal. In this way, when a breaker design has been fixed as capable of rupturing a certain current at

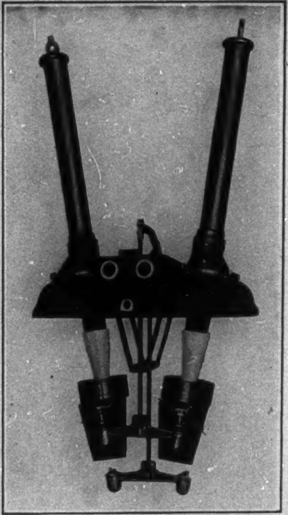


FIG. 4 [RANDALL]

Illustrates internal arrangement of 100,000-volt reactance breaker. Main contacts, having separated, and reactance coils, one concentrically mounted on each terminal, are in circuit. Final break is about to take place. Barriers separating main and breaking contacts are shown projecting below reactance coils. Sequence of operation is indicated in Fig. 5.

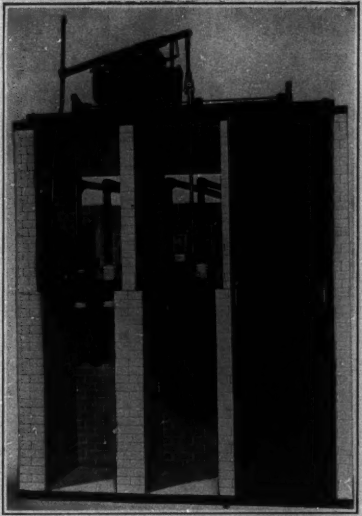


FIG. 6 [RANDALL]

Shows breaker intended for duty on high power system and is adapted to potentials up to 35,000 volts. Note arrangement of mechanism above, incorporating combined accelerating and retarding device as described in Figs. 7 and 8. This breaker illustrates present tendency in the extra strong one-piece drawn tank; heavy supporting bolts with steel fittings for same; provision for high acceleration vented air chamber above oil; oil level indicated by gage glass, vent obscured by mechanism; readily replacable arcing tips of liberal dimensions; individual pole units operated from single mechanism through common shaft.

a certain voltage, the kv-a. rating of the system to which it may properly be applied is one whose normal current rating is obtained by dividing the breaker current rating for the particular voltage by 6¼. Thus, a breaker rated at 160,000 kv-a., three-phase, 44,000 volts, contemplates 2100 ampere sper phase in the arc and may properly be applied to a station having a normal current of 335 amperes, 44,000 volts three-phase. All of this contemplates instantaneous tripping. If time tripping is employed, so that the current may have decreased to some smaller multiple of the normal value, application may be made to a still larger station, provided always that the maximum current to be terminated does not exceed the maximum volume given (in this case 2100 amperes). The time to reach the sustained short-circuit currents will vary widely; possibly from 15 to 50 cycles on 60-cycle systems, and from 5 to 20 cycles on 25-cycle systems. With time elements set for these periods or longer, the maximum duty on the breaker will approximate interrupting double current, and in general, for such installations the capacity of the plant may be at least doubled as against the safe application on instantaneous tripping.

The best method of specifying breaker equipment for a given service is to indicate the duty which the breaker will be expected to perform, by giving the maximum current that it may be called upon to interrupt, as well as the service voltage. It will be recognized, when this is done, that the source of power, method of tripping, or location on the system is immaterial, for all of those considerations are covered when the value for the maximum current is fixed. Some installations and classes of service may not warrant employing a design which will satisfactorily and repeatedly handle the worst short-circuit currents. For such installations, when the extreme maximum currents are very improbable and it is not desired to allow them, the usual maximum current which the breaker may be called upon to interrupt should be taken as the basis, and a breaker of such rupturing capacity specified.

The present tendency in circuit breakers is largely to improve mechanical details. Insulation of designs has generally been adequate. Among the notable mechanical features found in modern breakers are: (1) Increased strength of tanks with supports and fittings so as to withstand safely the shock of rupturing large powers. (2) Rapid acceleration of breaker so as to obtain high rates of contact separation with the attendant early termination of arcs, and consequent reduced energy dissipation. (3) Provision for vented expulsion chamber over the oil from which gases may escape, without entraining much oil, thus reducing the high and otherwise destructive pressures occurring in heavy duty.

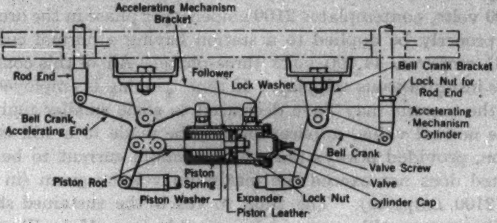

Accelerating Mechanism Bracket
Rod End
Follower
Lock Washer
Bell Crank Bracket
Lock Nut for Rod End
Bell Crank, Accelerating End
Accelerating Mechanism Cylinder
Bell Crank
Valve Screw
Piston Rod
Piston Spring
Valve
Piston Washer
Expander
Lock Nut
Cylinder Cap
Piston Leather

FIG. 7

This mechanism illustrates an arrangement commonly applicable to remote manually or electrically-operated breakers, and consists essentially of a spring for accelerating the opening of the breaker, with a plunger in a cylinder for retarding and bringing the moving contacts to rest without shock at the end of a stroke.

(4) Arrangement for liberal and easily replaceable contact parts of minimum cost, in even small as well as larger capacities. (5) Employment of larger capacity (single) pole units, suitably assembled, and operated from a single separate mechanism, instead of using multipolar units assembled with individual mechanisms.

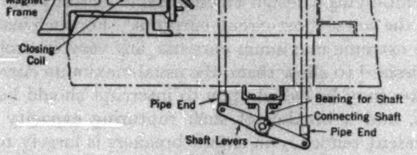

Accelerating and Dashpot Retarding Device
Main Lever
Hand Closing Bar
Pipe End
Trigger Lever
Trip Coil
Signal Switch
Magnet Frame
Closing Coil
Pipe End
Bearing for Shaft
Connecting Shaft
Pipe End
Shaft Levers

FIG. 8

This figure illustrates a typical solenoid mechanism for operating electrically controlled breakers, and incorporates the accelerating and dash pot devices shown in Fig. 7.

In existing practise, wide differences are found, and operating engineers sometimes seem to have almost opposite opinions. In one installation a breaker discharging a very small volume of oil accompanied by some smoke under the most severe conditions was considered as a hazardous application. On another system blowing off of breaker tanks was considered fairly serious, but principally because of the difficulty in replacing the distorted tanks. Mere discharges of smoke, oil, or distortion of the tank were looked upon as of trifling consequence, so long as the apparatus remained in operating condition. This brings up the question, frequently arising, "when is a breaker satisfactory for a given service?" One reply advocated that if the unit may immediately be put back into permanent satisfactory operation without immediate repair, it is proper for the particular application.

DISCUSSION ON "OIL CIRCUIT BREAKERS," (RANDALL), NEW YORK, FEBRUARY 17, 1915.

W. S. Franklin: There seems to me to be no justification for using a reactance in shunt with an oil circuit breaker rather than a resistance. We will assume that the heat developed in the shunt resistance wherever placed can easily be taken care of; so there can be no reason for using the reactance in place of the resistance because of the lesser amount of heat which may be developed.

On the other hand, the shunt resistance has some positive advantages over the shunt reactance because the second circuit breaker, which has to open the circuit after it has been established through the shunt reactance of the first, may operate when the current is high, and the energy stored in the shunt reactance will have to be taken care of.

My question is: Why use a shunt reactance rather than a shunt resistance when you arrange to operate two circuit breakers in series, in opening a circuit?

Philip Torchio: Why not put the reactance in series with the circuit breaker and eliminate the other circuit breaker?

W. S. Franklin: That is the way you do now.

Philip Torchio: Mr. Randall mentions in his paper that the volume of the oil and the pressure assist in breaking the arc. At the Turin Exhibition four years ago, a French firm had on exhibition some oil circuit breakers which operated under pressure. I do not remember whether they had any vent, or how they provided for that emergency. I would like to ask Mr. Randall whether they have made experiments and investigations along the line of having a positive pressure applied to the oil, and what results have been obtained.

H. R. Summerhayes: A large volume of oil is necessary for high-potential switches to get the distance for the insulation. For low-potential switches such as are used on city systems, if you try to get too large an oil volume it militates against the operating companies' requirements of small space. Furthermore, it introduces a larger volume of oil in the station; and of course we want to keep down the volume of oil as much as possible in the city stations.

Mr. Torchio's mention of an artificially created pressure is interesting, but it is doubtful whether it would be possible to create a higher pressure artificially in the time required than is actually created locally by the action of the arc itself.

In the paper it is stated that the simultaneous opening of several breaks will accomplish the intervention of a given oil distance more rapidly than will a smaller number of breaks. This assumes that the current is broken at the first zero point. When the circuit breaker is operating at or near its limit it does not break at the first zero point. However, the multi-break scheme is good.

Mention is made of the reactance switch, in which the two arcs are sprung at the same time, and one is shunted by reactance. It seems to me that here we have a multi-break switch—that is, two breaks in series,—plus a reactance; and by leaving out the reactance we will get better service. It seems obvious that there would be more drop across the arc, than across the arc and reactance in shunt with that arc.

I would like to ask if Mr. Randall finds that leaving out the reactance gives just as good results.

It is stated that modern operation, particularly on the score of simplicity, favors the solenoid action for electrically controlled oil circuit breakers. There is some difference of opinion among engineers on that point. There are large numbers of motor-operated switches in successful operation in which the actual opening and closing is done by a spring, the energy stored in the spring being supplied through a motor. Where, owing to its size and speed, the switch requires a considerable amount of power, the motor and spring combination may be preferable to the solenoid.

In reference to the question as to when a circuit breaker is a breaker and when it becomes a fuse, that is, the limit of its rating, that is a subject on which there has been a great deal of argument. Some breakers do not give any evidence of distress until the limit is reached, and then they go to pieces. Others show evidence of distress for a long time before the limit is reached, but never fail to break the circuit. The breaker itself may be injured, but the circuit is always broken.

P. M. Lincoln: I would like to answer one of the questions raised by Professor Franklin. He asked why resistance had not been used rather than reactance for the kind of breaker that takes two bites to do the job.

If Prof. Franklin will figure on the total amount of energy that a large system will cause to appear in such a resistance, even when it is allowed to attain its maximum permissible temperature, I think the final temperature he arrives at will be the answer as to why resistance is not used rather than reactance. The amount of material and the heating which takes place makes it impracticable to use resistance rather than reactance.

Philip Torchio: I would make a recommendation to the Standards Committee that they adopt the last specification given in the paper of Mr. Randall. That is, that for a particular application, a breaker is satisfactory for a given service if the breaker can be put back into permanent satisfactory operation without immediate repairs.

E. B. Merriam (by letter): We are greatly interested in the rapidity with which the contacts of an oil circuit breaker part. It is very difficult, however, to realize that there will be enough difference in the operation of commercial breakers on 25- and 60-cycle circuits to necessitate different types for these frequencies.

Too much emphasis should not be placed on the performance of gravity-actuated circuit breakers. Very few accepted designs using this and a number of other undesirable features brought out in the paper are operating at the present time.

Fig. 3 in the paper would be of more value if the speed were expressed in terms of some recognized unit, as percentages do not convey a concrete meaning.

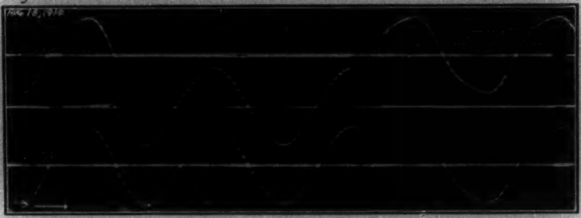
Reference is made to the benefit derived from the use of time-limit relays. This reference is made, of course, on the assumption that the short-circuit characteristics of most generators are similar.

The method which Mr. Randall states has been developed from experience, etc., in considering rupturing capacity is only of general use. It does not take into account the varying characteristics of individual generators nor of systems having a number of generators in multiple. It has been my experience that even though a generator equipment having 8 per cent impedance is assumed, the current at the time the switch opens may be anything less than 12½ times normal current. It may be 6¼ times normal current as an average, but it may also vary between very wide limits, even though the assumption is made that all the oil circuit breakers have their contacts part at the same time interval after the short circuit, or rather the abnormal load, comes on the system. This assumption may be correct for any one particular type of oil circuit breakers, but my experience indicates that this value is also variable throughout very wide limits.

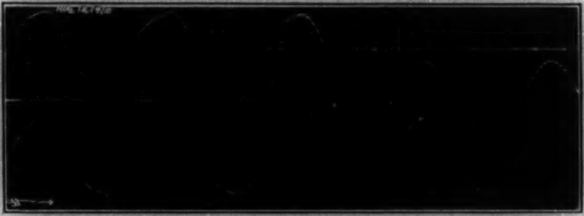
Mr. Randall mentions that there was no definite plan of rating or determining the capacity of circuit breakers available until recently. This is quite contrary to my experience, as the rupturing capacity of several of the principal lines of oil circuit breakers have been very well known ever since they have been placed upon the market, and considerable attention has always been paid to installations on large systems and those which presented unusual conditions. Now that the Standards Committee has recommended what seems to be a reasonable method of rating oil circuit breakers which has been adopted as standard by the Institute, it is to be hoped that all manufacturers will use this as a common basis.

Referring to the use of shunted reactances, experience indicates that while this scheme reduces the current that the oil circuit breaker must interrupt, it does not limit the actual drain on the system, nor does it protect feeders adjacent to the faulty one. Therefore it does not seem nearly so efficacious as when feeder reactances were used.

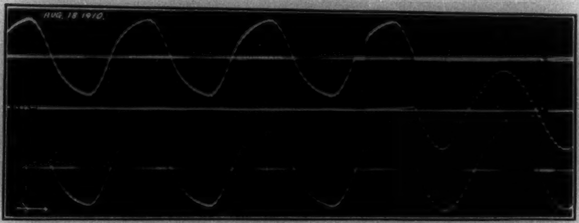
The point of failure of an oil circuit breaker is not a definite one. It varies through so wide a range of current at any given voltage that frequently honest differences of opinion may be held regarding it. A circuit breaker whose use is permissible on a power development where service interruptions and oil throwing may not seriously affect operating conditions would be considered



EFFECT OF ARCS UNDER OIL [MERRIAM]



EFFECT OF ARCS UNDER OIL [MERRIAM]



EFFECT OF ARCS UNDER OIL [MERRIAM]

unfit for service in a large central station where continuity of service and freedom from oil throwing are considered essential.

I am presenting herewith several oscillograms that may be of interest in connection with the study of electric arcs sprung under oil. In all of these the upper curve represents the current in the oil circuit breaker, the middle curve represents the pressure across the oil circuit breaker and the lower curve represents the pressure across the alternator supplying power for the tests. The oscillograms follow in general the reasoning laid down in Mr. Randall's paper.

The diagrams show the approximate limits through which the short-circuit characteristics of one particular class of alternators may be expected to vary. The characteristics will be different for alternators of different design and where more than one alternator is connected to the system under consideration.

In connection with Mr. Randall's paper the following references to papers previously presented to the Institute may be of interest.

The Modern Oil Switch, with Special Reference to Systems of Moderate Voltage and Large Ampere Capacity, (Cheney) A. I. E. E. TRANS. 1910, p. 1091.

Oil Circuit Breakers, (Merriam) A. I. E. E. TRANS., 1911, p. 495.

Some Recent Tests of Oil Circuit Breakers, (Merriam) A. I. E. E. TRANS. 1911, p. 1195.

The Use of Power-Limiting Reactances with Large Turbo-Alternators, (Schuchardt) A. I. E. E. TRANS. 1911, p. 1143.

Development of the Modern Central Station, (Steinmetz) A. I. E. E. TRANS., 1911, p. 1213.

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, (Burnham) A. I. E. E. TRANS., 1913, .p 731.

Notes on Oil Circuit Breakers for Large Powers and High Potentials, (Randall) A. I. E. E. PROCEEDINGS, October, 1913, p. 1885.

The Relation of Distribution Problems and Switching Apparatus, (Merriam) A. I. E. E. TRANS. 1914, p. 262.

C. Lichtenberg (by letter): The results of thousands of tests which we have made indicate that the principal feature of an oil for satisfactory service in oil circuit breakers is its ability to possess initially high dielectric strength and to retain it under adverse moisture conditions. This property appears to be important even in connection with oil circuit breakers operating on pressure as low as 400 volts, since we have found that a very small percentage of moisture in the oil will greatly reduce the circuit-interrupting capacity of the oil circuit breaker with which it is used.

Mr. Randall states that for very low temperatures a non-freezing oil should be used, but that most oils are unsatisfactory below 0 deg. or −10 deg. fahr. The temperatures given by Mr. Randall are slightly misleading as 0 deg.

if meant to have been measured by centigrade scale does not equal − 10 deg. on Fahrenheit scale.

The paper also contains the statement that non-freezing oils are usually so volatile at ordinary summer temperatures that under these conditions another oil must be used. It has been our experience, however, that oils can be obtained which will be suitable for use in oil circuit breakers for all temperatures between −40 deg. cent. and +60 deg. cent. They are, therefore, applicable for oil circuit breaker service throughout the most extreme range of temperatures experienced in North America.

Mr. Randall's paper leads one to believe that increasing the velocity with which the contacts of an oil circuit breaker part, by increasing the speed of the mechanism, is a more efficacious way of increasing the circuit-interrupting capacity of an oil circuit breaker than by increasing the number of breaks in series. This is in direct opposition to the conclusions we have reached as a result of a large number of tests. We have found that doubling the velocity with which the contacts of a particular oil circuit breaker part increases its circuit-interrupting capacity about 30 per cent, while doubling the number of series breaks will increase the circuit-interrupting capacity about 70 per cent. This result is directly explainable on the theory which I advanced some time ago concerning the operation of an oil circuit breaker. It states that the oil circuit breaker is a device for dissipating the stored electromagnetic energy of a circuit. It performs this function by converting this energy principally into heat which appears in the form of an arc at the oil circuit breaker contacts. If this arc is distributed between a large number of contacts, a greater rate of energy dissipation may be acquired and the circuit-interrupting capacity of the oil circuit breaker increased. If, on the other hand, the velocity with which the contacts of the oil circuit breaker part is increased, the time duration of the arc may be diminished but since the number of arcs is not increased, the rate of dissipation is not nearly so rapidly increased and consequently the circuit-interrupting capacity of the breaker is not nearly so high.

Throughout Mr. Randall's discussion, the acceleration of the contacts of an oil circuit breaker is frequently mentioned. It appears to me that the *velocity* with which the contacts of such a device part is more important than their *acceleration* at any particular point. It is also very noticeable that Mr. Randall continues to adhere to the fallacy that most oil circuit breakers are gravity-actuated. In reality, most oil circuit breakers are actuated through the most important portion of their travel by springs and not by gravity or solenoids or other electrically operated mechanisms. This factor is very important, since the time delay which may be introduced in the initial operation of an oil circuit breaker by a solenoid or other electrical mechanism is appreciable when compared with the time delay introduced by a spring or similar mechanism having a considerable amount of stored energy awaiting release for breaker operation.

Another very interesting thing in connection with oil circuit breaker study is the fact that if the conditions are properly selected, an oil circuit breaker may be made to start and complete the interruption of a given circuit at least one-fourth cycle before the current in that circuit would normally have passed through zero. This condition, however, is not a wise one to attain, since the results of numerous tests have indicated that the very sudden interruption of a circuit carrying even small current may produce excessively high pressure rises in that circuit, resulting in the destruction of the insulation, even though the energy present is comparatively small.

The proposed method for rating oil circuit breakers and specifying them follows in general the present A. I. E. E. rules. One important factor, however, which is omitted by the rules is also omitted in the paper, *i. e.*, the worst power factor of the circuit for which the breaker will be supplied. A hint of the effect of power factor is given in diagrams in the paper, but inasmuch as these are the results of theoretical analysis and no evidence is given that they are based on experimental data, complete reliance cannot be placed on them. It is known, however, that the power factor of a circuit has a very great influence on the duty to which the oil circuit breaker is subjected. The results of a great number of tests have indicated that a power factor of about 0.45 will more than triple the duty of an oil circuit breaker normally operating on a 0.98 power factor circuit. This result can be readily understood when it is considered that the power factor of a circuit is in most cases a measure of the stored electromagnetic energy in that circuit. Consequently, increasing the stored electromagnetic energy increases the energy which the breaker is called upon to dissipate.

F. W. Harris (by letter): Mr. Randall states: " Furthermore, neglecting the voltage peaks required for re-establishing the current, the maximum steady voltage attainable across an arc is limited, regardless of the length of arc or current volume, and hence, the same loss is developed regardless of the rate or length of opening, provided the current and time of arcing is the same. This is explained as follows. With practically any current encountered in serious breaker problems, the ionization in the arc space will be quite complete and, therefore, it will constitute an excellent conductor, becoming better as it is further heated by increased currents, so that the drop will remain practically constant independent of the current volume, provided it does not fall sufficiently to threaten deionization."

This might be differently stated as follows: (*a*) The voltage drop across the arc of an oil circuit breaker is quite independent of the length of that arc. (*b*) The voltage drop across the arc of an oil circuit breaker is quite independent of the current flowing through that arc.

Even explained as Mr. Randall has explained it, on the theory of ionization, it is hard to believe that his statement is correct, as it is contrary to our knowledge of arc phenomena. In the case of an ordinary arc the voltage drop across the arc increases much faster than the length and the voltage falls as the current is increased. I do not believe that an arc in oil is any different from any other arc in this particular.

In my opinion the action, when a circuit is opened by drawing an arc under a hydrocarbon oil, is purely a rectifying one. The introduction of the arc path into the circuit changes the current values very little, the resistance of the arc being small, often well below ten per cent of the total resistance of the circuit. On relatively heavy short circuits on an 11,000-volt circuit the maximum observed drop through the four breaks of a standard circuit breaker is often less than 1000 volts. At the instant that the current reaches zero we have a low resistance and a moment after we have an infinite one if the breaker opens the circuit.

In considering circuit breaker action we must understand the conditions that exist just after the current reaches zero. We have had a low-voltage high-current arc passing through a hole in the hydrocarbon oil. This hole is filled with metallic vapor and with burnt oil. The burnt oil is in the form of hydrocarbon vapors, such as methane, CH_4, and lower hydrocarbons with probably some free hydrogen and perhaps some carbon in gasified form. The metallic and carbon vapors are good conductors, the hydrocarbon and hydrogen vapors are not. Whether the arc establishes itself or not depends on three things: First, the length of the vapor path; second, the specific conductivity of the vapor path; and third, the voltage available to force current over that path. The crisis is essentially the same as that faced by the alternating-current arc lamp 120 times a second. The arc lamp, however, continues to arc over where the circuit breaker opens the circuit. In any circuit breaker the length of arc and voltage available are such that an ordinary arc in air would hold indefinitely. It is in the specific conductivity of the vapor path that the secret of oil circuit breaker action lies. The vapor path acts like a check valve resisting reversal of the current direction. I believe this valve action is due to a preponderance of hydrogen in the vapor path.

In breakers having a considerable number of breaks in series each break is a law unto itself. As the resistance of each break is small the current flowing is determined by external conditions and not by arc conditions. The current being fixed by external conditions, the energy in each arc path is determined almost wholly by the length of that path. It is practically impossible to set multiple contact breakers so that all breaks open at once. The result is that the first break to open absorbs nearly all the energy, the other arcs being short and of much lower voltage. Consequently the conditions for preventing reversal will differ widely among the various breaks, one or more breaks being generally quite favorably situated at the instant of reversal. The ideal circuit breaker would break the circuit at the instant of current reversal and the more breaks you have in series the more likely one of them is to be ideally situated at that instant. I have had some experience with both the resistance and the reactance breakers, having had some share in initiating this development, and I cannot help feeling that an increase in the number of breaks in series would go a long way towards solving the breaker problem without the necessity of the more complicated reactance type. Mr. Randall evidently feels that the multiple break type will involve complications of structure not met with in the reactance breaker, but such is not a fact. Such multiple break circuit breakers can undoubtedly be made as compact and quite as efficient as the reactance type.

K. C. Randall: Replying to Mr. Franklin, reactance is preferable to resistance because it takes less space, is cheaper, and satisfactory for the purpose.

Replying to Mr. Torchio, series reactance is satisfactory for some applications but often the drop, always present across the reactance, is not desirable, and on such circuits from heavily powered systems the reactance type of breaker may be required.

Replying to Mr. Summerhayes, some years ago tests of arcs established under pressure showed qualitatively an advantage from the pressure.

Mr. Merriam's contribution is of particular value, coming from an experienced circuit breaker engineer. The reference to papers previously presented on this general subject is also timely.

In regard to series reactance, it may be noted the value of the series reactance in feeder circuits has been generally well recognized as the protection to service on adjacent feeders. Sometimes, however, the value of the reactance required to make circuit breaking easy or even safe is not available nor permissible as a permanent series arrangement. Here the reactance breaker finds a good application.

The author is glad to note essential concurrence in an engineer of Mr. Lichtenberg's broad experience and also acknowledge the additional data which he contributes.

The slight error in referring to the oil temperature in the paper does not make plain that a range from zero deg. fahr. or minus 10 deg. fahr. was the lower limit for most oils, although, as Mr. Lichtenberg points out, oil suitable for breaker work throughout a much wider range is available.

I can hardly agree with Mr. Lichtenberg that essentially " the oil circuit breaker is a device for dissipating the stored electromagnetic energy of the circuit." It is true that energy is dissipated in the tank when a breaker operates under load, and as generally acknowledged, the less energy there may be, the less danger from destruction, for experience has well proved that violent explosions—dissipation of enormous energy—are the usual causes of oil breaker failures. From this it is apparent that rather than designing to increase the amount of energy that may be dissipated within the breaker tank, the endeavor should be to decrease this amount of energy, for in so doing any given strength of construction will be adequate for increased duty, or a given duty can be handled with a lighter unit.

It seems to me that an oil breaker could be better described as a device for establishing a dielectric of essentially infinite value in a circuit otherwise capable of carrying current. A breaker of infinite opening speed would cause most of the stored energy to dissipate in the circuit; that is, outside of the tank. A slow breaker might allow not only the stored energy but additional energy from the power supply to dissipate within the tank (until destruction). In general, the less energy dissipated the less the chance of damage, as is obvious. Any plan whereby the necessary dissipation of energy within the breaker tank can be reduced will operate to increase the rupturing capacity, and vice versa. Consideration of these facts leads the author to have confidence in a highly accelerated breaker which—as is acknowledged by Mr. Lichtenberg—tends to diminish the time of the arc, and hence the amount of energy dissipated, which is the desired result.

The ideal circuit breaker terminates the current close to the normal first zero after the contacts separate. Increasing the rate of contact separation tends to hasten the current termination and also to prevent reestablishment, owing to the greater oil distance separating the contacts. All of these considerations clearly show the advantage of the highly accelerated and therefore rapidly opening breaker. However, for some applications the multi-gap design may be useful. The evil result of too fast opening, causing premature termination of current (before normal zero), is quite properly emphasized and again illustrates where a highly accelerated double-unit breaker with one member shunted by reactance finds excellent application. Such a unit built up of members of modest individual capacity will be suitable for service on rather large power, because the operation is to first reduce the current to a satisfactory low value and then interrupt it with little, if any, line disturbance.

It might be further added that the current which circuit breakers are required to rupture is almost invariably determined by the characteristics of the circuit and not by the breaker. Therefore, increasing the number of arcs within the tank means a corresponding increase in the amount of energy to be dissipated, while terminating the current by a single breaker will be accompanied by a minimum dissipation of energy within the tank and at the same time, if highly accelerated, afford greater assurance that re-establishment after the first zero will not occur.

The author finds an apparently general concurrence in Mr. Harris's discussion, although viewed from a different point and expressed on a different basis.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 17, 1915, under the auspices of the High-Tension Transmission Committee.

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COMPARISON OF CALCULATED AND MEASURED CORONA LOSS CURVES

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

Corona loss curves made on a number of experimental and practical lines by different investigators have been corrected and plotted. The loss has been calculated by the quadratic law for each case under the same conditions as to spacing, conductor diameter, altitude, etc., and plotted for comparison.

It is of interest to note that the measured values were made in various parts of the country. The time period covers a number of years and the altitude varies from sea level to 10,000 ft. An exact check of calculated and measured losses cannot be expected, as the exact conditions of conductor surface, the wave shape, etc. are not always known. Such losses are also difficult to measure, especially on practical lines where the voltage range is quite small and there is a large number of corrections to make. The check is as close as the accuracy of the measurements permits. The variations from the calculated values are in most cases due to the fact that practical measurements have been made on the unstable part of the curve below the visual critical voltage value. The losses at this part of the curve are fully discussed.

CORONA loss curves made on a number of experimental and practical lines have been collected and plotted. The loss has then been calculated by the quadratic law for each case, under the same conditions as to spacing, conductor diameter, altitude, etc., and plotted for comparison. In all cases the full lines in the illustrations represent the calculated curves, while the broken lines represent the measured curves.

It is of interest to note that the measured values were made at various parts of the country, by independent investigators, and that the time period is a number of years. The altitude varies from sea level to 10,000 ft. An exact check of calculated and measured losses can not be expected, as the exact conditions of conductor surface, the wave shape, etc., are not always known. Such losses are also difficult to measure, especially on practical lines, where the voltage range is quite small and there are large corrections to make. In most cases, when such loss curves on practical lines have been given, measurements have not been carried above the ***visual critical corona point.***

Before an examination of the curves is made, attention is called to the following summary of facts which are fully discussed in *The Law of Corona*—I.*

The law of corona takes the general form

$$p = c\,(e - e_0)^2$$

which means that under conditions otherwise constant, the loss varies as the square of the applied voltage, above a certain critical voltage, e_0 or e_d. Figs. 1 and 2 show characteristic curves. The critical voltage, e_0, is called the ***disruptive critical voltage.***

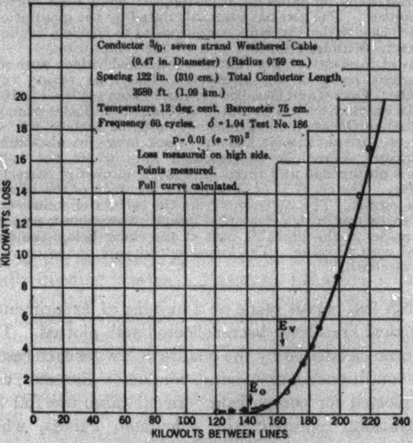

FIG. 1—OUTDOOR SINGLE-PHASE EXPERIMENTAL LINE. (TESTS MADE BY F. W. PEEK, JR., SCHENECTADY, 1910)

Visual corona does not start at the ***disruptive critical voltage***, but at some higher voltage e_v, the visual critical voltage. Both of these voltages have been calculated and marked on the curves. Theoretically, if the conductors were perfectly smooth, no appreciable loss should occur until the visual critical voltage, e_v, is reached, when the loss should suddenly take a definite value. For e_v, and higher voltages, the loss should follow the quadratic law.

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*TRANS. A. I. E. E., 1911, p. 1889. See also *Law of Corona—II*, TRANS. A. I. E. E., 1912, p. 1051; and "High Voltage Engineering," *Journal* of Franklin Institute, December, 1913.

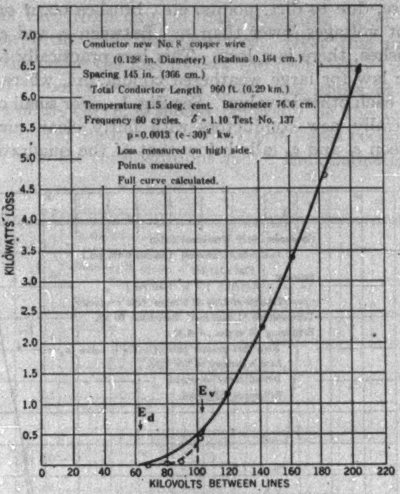

FIG. 2—OUTDOOR SINGLE-PHASE EXPERIMENTAL LINE. (TESTS MADE BY F. W. PEEK, JR., SCHENECTADY, 1910)

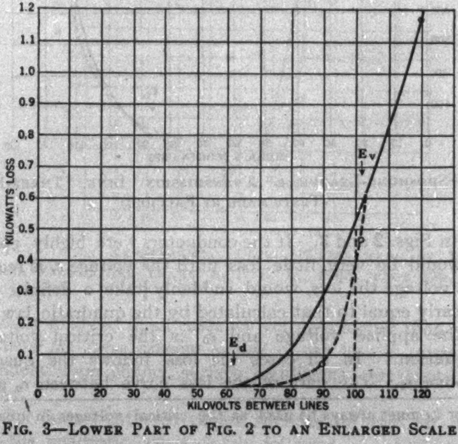

FIG. 3—LOWER PART OF FIG. 2 TO AN ENLARGED SCALE

In practise, due to dirt, points, etc., brushes occur on the conductors at voltages lower than e_v. Between e_v and e_0, due to these brushes, there is a loss. This loss practically follows the quadratic law for large weathered conductors, where e_v and e_0 approach each other in value. See Fig. 1. For small conductors and especially new conductors with fairly clean surfaces, the loss between e_v and e_0 falls below that of the quadratic law, as shown in Figs. 2 and 3. If the conductors were highly polished there would be very little loss until the voltage e_v is reached. At this voltage the loss would suddenly take a definite value very nearly equal to that calculated by the quadratic law with e_v as the applied voltage and e_0 as the critical voltage in the equation.* In all cases the loss follows the quadratic law above e_v. The part of the loss curve between e_0 and e_v

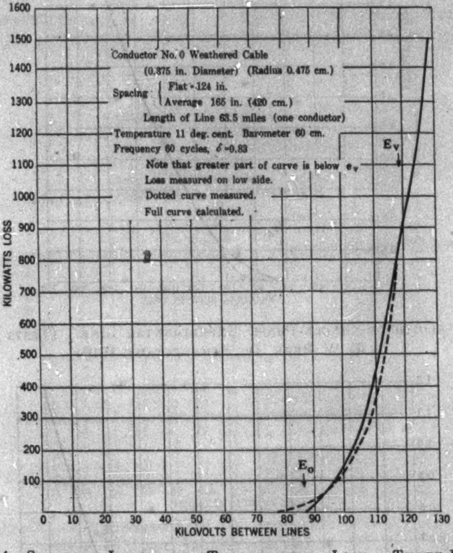

FIG. 4—SHOSHONE-LEADVILLE TRANSMISSION LINE, THREE-PHASE. (TESTS MADE BY FACCIOLI)

will thus vary from day to day-depending upon the chance condition of the conductor surfaces. Over this unstable section of the curve the loss follows the probability law. It is of practical importance only to know the limits of the loss at this part of the curve; e_o should generally be the limit of voltage on practical lines, as otherwise storm losses become excessive.

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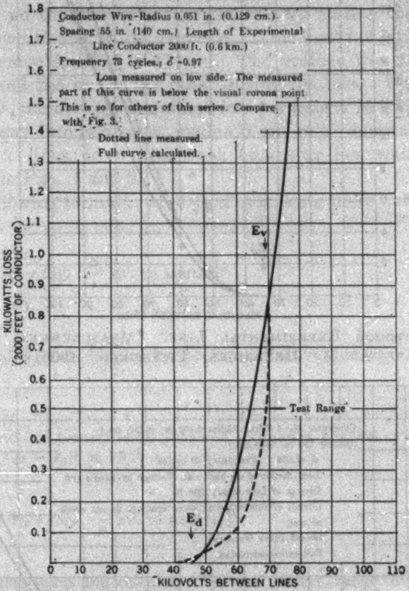
* e_0 or e_d must always be used as the critical voltages in quadratic law.

Thus, from the considerations above, the quadratic law should



Conductor Wire-Radius 0.051 in. (0.129 cm.)
Spacing 55 in. (140 cm.) Length of Experimental
Line Conductor 2000 ft. (0.6 km.)
Frequency 78 cycles.; δ = 0.97
Loss measured on low side. The measured part of this curve is below the visual corona point. This is so for others of this series. Compare with Fig. 3.
Dotted line measured.
Full curve calculated.

FIG. 5—OUTDOOR EXPERIMENTAL LINE. (TESTS MADE BY MERSHON, NIAGARA FALLS). (SEE TRANS. A. I. E. E., 1908, PAGE 876, FIG. 27)

be closely followed in all cases for voltages higher than e_v. For *the part of the curve between* e_v *and* e_o the loss is unstable and dependent upon chance surface conditions, dirt spots, etc., as follows:

1. For large weathered cables, such as are used in practical lines, the quadratic law is closely followed.

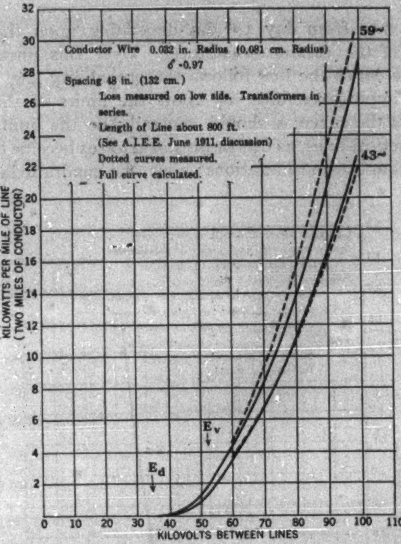


FIG. 6—OUTDOOR EXPERIMENTAL LINE. (MEASUREMENTS MADE BY A. B. HENDRICKS, PITTSFIELD, 1906)

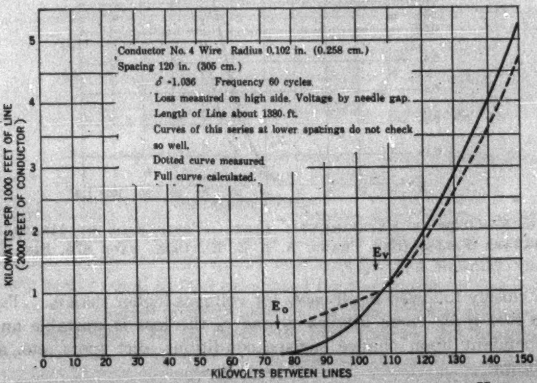


FIG. 7—OUTDOOR EXPERIMENTAL LINE. (TESTS MADE BY HARDING, PURDUE UNIVERSITY). (SEE TRANS. A. I. E. E. 1912, PAGE 1035)

2. For new conductors, and especially small ones, the loss at voltages lower than the visual critical voltage, e_v, falls below the quadratic law.

Figs. 1 and 4 are typical of condition (1), while Figs. 2 and 5 are typical of condition (2).

Figs. 1 to 7 show a remarkably good check between calculated losses and data available from measured losses. Another check, which is given in the N. E. L. A. *Bulletin* for June, 1912, * might be mentioned here. This paper states that the loss roughly measured on the Eastern Michigan line by station instruments was between 15 and 20 kw. per mile. This line is of No. 0 copper at an average spacing of 174 in. The voltage was 140 kv. at one end and 165 kv. at the other during the test. Under these conditions, the average calculated loss per mile is 15 kw.

The many hundred tests, made on our experimental outdoor and indoor lines, from which the quadratic law was derived, check as in Figs. 1 and 2.

The following formulas were used in making these calculations:

Visual Corona.

$$e_v = m_v g_v r \log_e \frac{S}{r} \text{ kv. to neutral}\dagger$$

$$g_v = 21.2\,\delta\left(1 + \frac{0.301}{\sqrt{\delta r}}\right) \text{ kv. per cm. (effective sine wave)}$$

Corona Loss.

‡For practical transmission lines and frequency near 60 cycles:

$$p = a\,f\,(e - e_0)^2 \times 10^{-5}$$

$$e_0 = m_0\,\delta g_0\,r \log_e \frac{S}{r} \text{ kv. to neutral}\dagger$$

§For small wires and calculation over a greater range of frequency, etc:

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*G. Faccioli, " Corona on High-Tension Lines," N. E. L. A. *Bulletin*, June, 1911.

†Kilovolts between lines divided by 2 for single-phase and $\sqrt{3}$ for three-phase.

‡*Law of Corona—I and II*, TRANS. A. I. E. E., 1911 and 1912.

§"High-Voltage Engineering," F. W. Peek, Jr., Franklin Institute, December, 1913.

$$p = 241\,(f + 25)\sqrt{\frac{r + \frac{6}{S} + 0.04}{S}}\,(e - e_d)^2 \times 10^{-5}$$

$$e_d = m_o\, g_d\, r \log \frac{S}{r}$$

$$g_d = g_o\delta\left(1 + \frac{0.3}{\sqrt{\delta r}}\,\frac{1}{1 + 230\, r^2}\right)$$

The probability law

$$p_1 = q\epsilon^{-h(e_0 - e)^2}$$

where

p = loss in kilowatts per kilometer of a single-line conductor.
e = effective value of the voltage between line conductors and neutral in kilovolts.
f = frequency.

$$a = \frac{344}{\delta}\sqrt{\frac{r}{S}}$$

r = radius of conductors in cm.
S = spacing between conductors in cm.

δ = air density factor $= \dfrac{3.92\, b}{273 + t}$ b = barometer in cm. t = temperature deg. cent.

g_o = 21.2 kv. per cm. effective sine wave.
m_o is a constant dependent upon the surface condition.
m_o = 1 for polished wires.
m_o = 0.98 to 0.93 for roughened or weathered wires.
m_o = 0.87 to 0.83 for cables.
m_v = m_o for wires.
m_v = 0.82 part corona, 0.72 complete corona } cables.

Discussion on "Comparison of Calculated and Measured Corona Loss Curves" (Peek), New York, February 17, 1915.

J. B. Whitehead. Mr. Peek states that in the case of clean wires his losses would begin at the voltage E_v, rising abruptly from 0 to the values shown for their voltages on the curves. As I understand it this voltage E_v is that at which corona breaks out on clean wires and is calculated from the now well known expression involving the diameter of the wire and the distance between wires.

We are indebted to Mr. Peek for many valuable observations on corona losses. Engineers must, of necessity, turn to his work in their provision against this important limitation of high-voltage transmission. He has from a large number of curves deduced the empirical formula given in the paper for calculating values of corona losses.

Mr. Peek notes, as already stated, that the loss on smooth wires would begin at the voltage E_v, rising rapidly from 0 value to that given by his curves of observation. He finds, however, in his curves from observation that the loss continues below the voltages E_d, which are lower than E_v by varying amounts. Mr. Peek tells us that these losses below the voltage E_v are due to dirt and other surface irregularities. If I understand his paper correctly it is his claim that these irregular losses, due to imperfections, may also be calculated by means of his formula. I should like to ask Mr. Peek why, if these losses below E_v are due to such indeterminate factors, we should attempt to tie them in with a definite law. As a matter of fact, the curves of observed losses below E_v as given by Mr. Peek do not appear to have any definite relation whatever to the calculated curve. In Fig. 1, the observed losses extend far below the value E_o, in Figs. 2 and 3 they start well above E_d, in Figs. 4 and 5 they again start below E_d. In Figs. 6 and 7 we cannot tell where they cross the 0 line, although in the latter case we have evidence of most erratic behavior.

I heartily concur with Mr. Peek that on clean wires there would be no loss below the critical corona-forming voltages E_v. Indeed all measurements of precision prove this beyond doubt. I should much prefer, however, to take care of the existence of losses in actual transmission lines at voltages below E_v by the use of an engineering factor of safety rather than by any attempt to include indeterminate and variable factors in a rigid formula.

In my opinion the losses on smooth wires would begin at E_v, not with a sudden increase to a value represented by any one of Mr. Peek's curves, but from 0 rising gradually and in a uniform curve and perhaps coinciding with Mr. Peek's curve at some voltage well above E_v. The entire area between this theoretical curve and a curve of observation as given by Mr. Peek would then be due to surface irregularities, weathering, etc. This area would therefore vary widely in different circumstances, and its influence on design should therefore be taken care of by a factor of safety.

Philip Torchio: I ask Mr. Peek if the law of 30 kv. per cm. gradient would hold in layers of insulating materials where the distances may be very small.

F. W. Peek, Jr.: I would like to state again that the calculated losses and the losses measured on practical lines cannot be expected to check exactly, especially on the lower part of the curve. This is so because of the difficulty of making such measurements on long practical lines. It is generally necessary to make these measurements on the low side of the step-up transformer, and the wave shape, barometric corrections, etc., are not always actually known. The check obtained here is as close as the accuracy of the measurements on practical lines permits.

The disruptive critical voltage, e_0, which Dr. Whitehead has referred to in his discussion, was not determined by a single reading on the unstable part of the curve, but it was determined from readings extending over the whole curve. Hundreds of corona loss curves were carefully made on the experimental line. These curves were measured on the high side, and all corrections were actually known. It was found that above the visual critical corona voltage these curves obey a quadratic law, thus:

$$p = k\,(e - e_0)^2$$

Therefore, if $\sqrt{p}$ and e are plotted, a straight line cutting the e axes at e_0 results. Thus, as already stated, e_0 was not determined by a single reading on the lower part of the curve, but by the whole curve over a range of voltage in some cases as much as 20 times as high as the critical voltage. The gradient corresponding to the e_0 voltage is always 30 kv. per cm. maximum, the strength of air. Losses at the lower part of the curve are fully discussed in my papers.

Mr. Torchio has asked if the voltage gradient required to start corona, or cause spark-over at very small spacings, is greater than at large spacings. The apparent strength of air increases very rapidly after the spacing is decreased below a given minimum value. The minimum value dpends upon the shape and size of the electrodes. For spheres it is 0.54 $\sqrt{R}$ cm., where R is the sphere radius in cm. This subject is fully discussed in my paper of June, 1913.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 17, 1915, under the auspices of the High-Tension Transmission Committee.

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A 100,000-VOLT PORTABLE SUBSTATION

BY CHARLES I. BURKHOLDER AND NICHOLAS STAHL

Abstract of Paper

Expanding needs of the Southern Power system, paralleled many miles by railroads, required a flexible-connection transformer relay of large capacity, easily portable, and self-contained on a single car. The equipment in operation is of 4000 kv-a. actual capacity, and provided with high- and low-tension switch gear, instruments, panel, wiring and cables, oil-insulated, self-cooled transformers with motor-driven blower for forced air draft, special means of establishing the high-tension delta with 100,000-volt clearances, after transformer terminals and high-tension switches have been raised by a portable derrick from receptacles where all fragile parts are protected from malicious tampering. Besides meeting standard freight car requirements for transportation, substantial, specially braced trussed superstructure is provided for supporting cabs and switch gear, which latter, as well as transformer terminals, must be lowered, during transit, to meet railroad clearances. Unusual flexibility of voltage connections is secured, contributing largely to the successful operation.

Current for lights, instruments and blower motor is obtained from auxiliary transformer windings incorporated with the main units.

Low-tension arrangements allow operation at various voltages with minimum switching.

The entire equipment is designed for simplicity and dispatch in disassembly for transit, and reassembly in new location.

IN JULY, 1914, there was put into service on the system of the Southern Power Company a portable transformer substation, unique in several respects, particularly so in the actual capacity of 4000 kv-a. and in the adaptation of the apparatus for operating voltages as high as 100,000.

The idea originated from the growth of the Southern Power Company, the need for some means of extending, at will, the connections of the system, and the somewhat unusual transportation facilities along its transmission lines.

At present, about 1000 miles of 100,000-volt circuits are in operation, with nearly 550 miles more of 44,000-volt lines, besides perhaps 90 miles at 13,200 volts and the regular distribution circuits at 2200 volts. The high-tension circuits are connected in the multi-meshed network shown on the map, Fig. 1. The connected transformer capacity, step-up and step-down, is approximately 365,000 kv-a. Closely parallel to these circuits run, for an aggregate distance of about 700 miles, one or more of the following railroads: Southern, Seaboard Air Line, Atlantic Coast Line, Piedmont & Northern, and Clinchfield, thus offering a tempting opportunity, denied to transmission systems remote from railroad facilities, for the use of a portable substation equipped to serve a variety of purposes, especially as the territory served contains many mills and towns along the right of way, where sidings are available.

FUNCTIONS

Such a station must be capable of supplying adequate transformer relays for the following uses:

1. Spare capacity for even the largest stations.
2. Temporary replacement of a distributing or tie-in substation being enlarged or rebuilt.
3. Break-down replacement of a substation.
4. Emergency stand-by service to or from neighboring transmission companies, central stations or isolated plants.
5. "Pioneer service" at town or mill, pending the determination of the proper permanent substation equipment.
6. Tentative service for mill or other prospective customer.
7. "Power solicitor service" with those needing power immediately.
8. Miscellaneous emergencies.

REQUISITE CHARACTERISTICS

To perform these functions satisfactorily, the equipment must (*a*) admit of transport over standard steam and electric railways, *i.e.*, not exceed the limiting dimensions and weights involved in passage through tunnels, over bridges or under tracks; (*b*) make such parts as would, in service, extend beyond railroad clearances, capable of easy and rapid disassembly and, after transport, similar reassembly ready for operation in the new location; (*c*) insure obtaining suitable nominal voltage for both transmission and distribution circuits; (*d*) admit of varying these nominal voltages by moderate gradations to meet line-drop conditions at various places; (*e*) furnish suitable high- and low-tension switch gear, instruments and metering devices; (*f*) protect fragile parts from damage by malicious mischief,

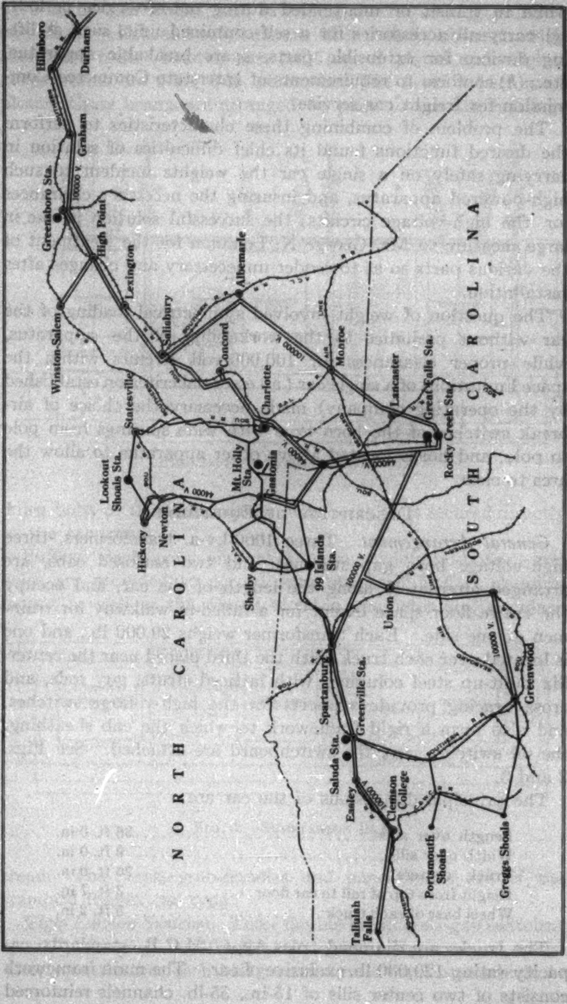

Hillsboro
Durham
Graham
Greensboro Sta.
100000 V.
High Point
Winston-Salem
Lexington
Albemarle
Salisbury
Concord
Monroe
100000 V.
Statesville
Charlotte
Lancaster
Great Falls Sta.
Rocky Creek Sta.
Lookout Shoals Sta.
Mt. Holly Sta.
Gastonia
44000 V.
44000 V.
44000 V.
Hickory
Newton
99 Islands Sta.
Shelby
Union
100000 V.
Spartanburg
Greenville Sta.
Greenwood
100000 V.
Saluda Sta.
Easley
100000 V.
Clemson College
Portsmouth Shoals
Greggs Shoals
Tallulah Falls
NORTH CAROLINA
SOUTH CAROLINA
SOUTHERN
SEABOARD
A.C.L.

FIG. 1—TRANSMISSION SYSTEM OF SOUTHERN POWER CO.

while in transit or unattended during out-of-service periods; (*g*) carry all accessories for a self-contained unit, such as lifting devices for extensible parts, spare breakable apparatus, etc.; (*h*) conform to requirements of Interstate Commerce Commission for freight car service.

The problem of combining these characteristics to perform the desired functions found its chief difficulties of solution in carrying safely on a single car the weights incident to such high-powered apparatus, and insuring the necessary clearances for the high-voltage circuits; the successful solution is due in large measure to Mr. George N. Lemmon for the treatment of the various parts so as to render unnecessary any changes after installation.

The question of weight involved symmetrical loading of the car without prejudice to the workability of the apparatus, while proper clearances for 100,000-volt circuits within the space limitations of a single car (an essential criterion established by the operating company) made necessary the choice of air-break switches of the horn type with wide spacings from pole to pole, and horns located above other apparatus to allow the arcs to clear.

Description of Equipment

General Arrangement. Three 1000-kv-a. transformers, three high-voltage horn gap switches, and two enclosed cabs, are arranged alternately along the length of the car, and occupy the entire floor space except for a railed-in walkway for trainmen at one side. Each transformer weighs 29,000 lb., and one is located over each truck, with the third placed near the center. Six built-up steel columns, with latticed struts, guy rods, and cross bracing, provide supports for the high-voltage switches, and also form a rigid framework to which the cab sheathing, the oil switches, and the switchboard are attached. See Figs. 2 and 3.

The principal dimensions of the car are:

Length over sills	38 ft. 0 in.
Width over sills	9 ft. 0 in.
Truck centers	26 ft. 0 in.
Height from top of rail to car floor	3 ft. 7 in.
Wheel base of each truck	5 ft. 2 in.

The trucks are diamond truss type, M.C.B. standards, capacity rating 120,000 lb. exclusive of car. The main framework consists of two center sills of 15-in., 55-lb. channels reinforced by 3-in. by 3-in. angles, and extending the whole length of the car, 38 ft. End and side sills are 12-in., 40-lb. channels with side truss rods. Bolsters are built up of plates and angles. Cross beams are 6-in., 8-lb. channels. The floor is ¼-in. steel plate. Cross beams are arranged in pairs to suit the holding-down bolts of the transformers, which are thus secured directly to the car frame.

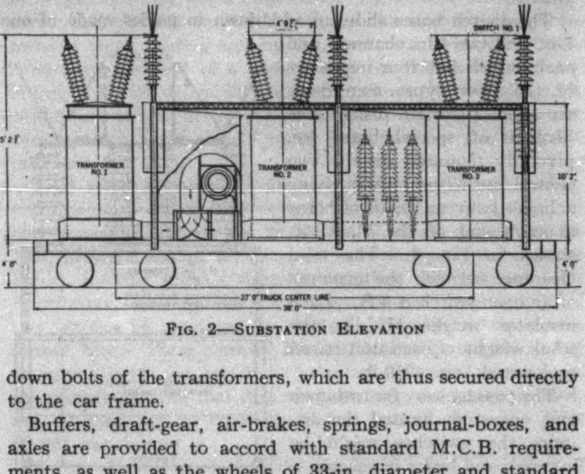

4' 9½"
SWITCH NO. 1
15' 2½"
TRANSFORMER NO. 1
TRANSFORMER NO. 2
TRANSFORMER NO. 3
10' 2"
4' 0"
4' 0"
27' 0" TRUCK CENTER LINE
38' 0"

FIG. 2—SUBSTATION ELEVATION

Buffers, draft-gear, air-brakes, springs, journal-boxes, and axles are provided to accord with standard M.C.B. requirements, as well as the wheels of 33-in. diameter and standard tread. The steps, grab-handles and hand-brakes are of the standard freight car type.

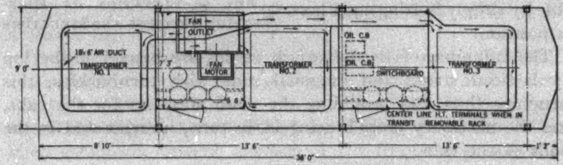

FAN OUTLET
18×6" AIR DUCT
TRANSFORMER NO. 1
9' 0"
7' 3"
FAN MOTOR
6' 6"
TRANSFORMER NO. 2
OIL C.B.
OIL C.B.
SWITCHBOARD
TRANSFORMER NO. 3
CENTER LINE H.T. TERMINALS WHEN IN TRANSIT REMOVABLE RACK
8' 10"
13' 6"
13' 6"
1' 2"
38' 0"

FIG. 3—SUBSTATION PLAN

High-Tension Switches. Three double-break horn-gap switches, specially designed for 100,000-volt service, are arranged transversely on the car, each being carried on a steel base which, to secure proper clearance height for the horns, slides vertically inside the main columns, and can be raised or lowered by means of two small windlasses, operated by men stationed at each side of the car. Simultaneous service operation of the switches is obtained by means of a pipe rod connected to a crank on each switch.

The switch bases slide up and down in guides made of one 7-in. and two 4-in. channels, and each switch has four insulators of the post type, comprising six 14-in. porcelain disks. The blade is of special brass tee, pivotally mounted on the two central insulators, thus giving a break between a pair of horns at each end of the blade, as shown in Fig. 4. The total clearance between the terminals of an open switch is 6 ft. Each insulator weighs 175 lb., the total weight of each unit raised or lowered being 950 lb.

The passage-way for trainmen and operators limited the distance the switches might be lowered, and hence it was necessary to make the horns detachable by simply bolting each horn in position.

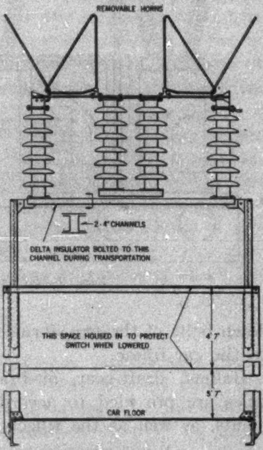

REMOVABLE HORNS
2-4" CHANNELS
DELTA INSULATOR BOLTED TO THIS CHANNEL DURING TRANSPORTATION
THIS SPACE HOUSED IN TO PROTECT SWITCH WHEN LOWERED
4' 7"
5' 7"
CAR FLOOR

FIG. 4—ELEVATION OF HIGH-TENSION SWITCHES AND STRUCTURE

The columns serving as switch guides are braced at the top by latticed struts and diagonal rods with turnbuckles, this structure thus also providing the main supports for the cabs, and the necessary cross-bracing is, in turn, incorporated in the walls of the cabs.

High-Tension Delta. To establish the high-tension delta with sufficient clearance for 100,000-volt operation, the second and third transformer terminals shown in Fig. 8 (counting from the left) are connected directly to the inboard end of the middle switch, while the fourth and fifth terminals similarly connect with the right-hand switch, the first terminal joining the left-hand switch directly, and the delta is closed by bringing to this switch a lead from the sixth terminal by means of two post-type insulators with special bases which hook over the latticed strut so that the insulators lean outwardly at an angle of about 45 deg., and require no bolts for proper support.

Transformers. For obvious reasons, oil-insulated, self-cooled transformers were the only admissible type. Space limitations in height, however, were imposed by tunnel and bridge clearances, and likewise in width both by the necessity for symmetrical truck loading and by the Interstate Commerce Commission requirement of a passage-way for trainmen; similarly in length, by the desirability of keeping down the over-all length of the car, as well as by considerations of normal transformer design, which apply also to undue proportions in the other dimensions.

Thus arose the necessity for provision of additional cooling arrangements, which were secured by a 20-h.p. motor-driven blower having capacity for 20,000 cu. ft. of air per minute at 1 oz. pressure, forcing air from the cab, shown on the right in Fig. 8, through suitable ducts surrounding the base of each transformer, and up along the corrugations. The supply of this air can be regulated by shields or screens at the transformer base. These screens are adjustable in height, acting as valves to the air, which, as experiment shows, closely hugs the corrugations, so that it is not necessary, for adequate cooling, to carry up an enclosing casing further along the sides of the transformer.

A hinged portion of the cab sheathing, which is padlocked shut in transit, is open when in service, and serves as an awning-like protection for the blower intake, while allowing free access of air to it.

To allow transport through tunnels and under bridges, it is necessary to house the transformer terminals, and to lower the high-tension switches. In the case of the transformer terminals, this is accomplished by rigging from the latticed strut structure, forming the top of the framework above the car, a wooden derrick, the parts of which are carried as car equipment. With this derrick the terminals are lowered through openings in the tops of the cabs, where special steel racks are provided for these terminals, including sheet steel cylinders, which cover the ends of the terminals normally under oil, and prevent the entry of moisture to the condenser type bushings.

Flexibility of Connections. It is possible to secure the following high-tension voltages:

100,000
96,533
93,066
89,600
86,800
86,133
83,333
82,666
79,866
79,200
76,400
73,600
72,933
70,133
69,466
66,666
66,000
63,200
60,400
59,733
56,933
56,266
53,466
52,800
50,000
47,200
46,533
43,733
43,066
40,266
39,600
36,800
34,000
33,333
29,866
30,533
27,066
26,400
23,600
20,133
16,666
13,200

The current-carrying capacity of the windings is such that 28 out of these 42 possible high-tension arrangements can be used with rated capacity output from the transformer (1000 kv-a.) without exceeding, in continuous operation, a temperature rise of 40 deg. cent.

Low-tension windings provide for full capacity output at 2200, 4400, 6600 and 13,200 volts.

Therefore, out of the 168 possible ratios of transformation, 112 of these combinations can be secured with full capacity of the transformer.

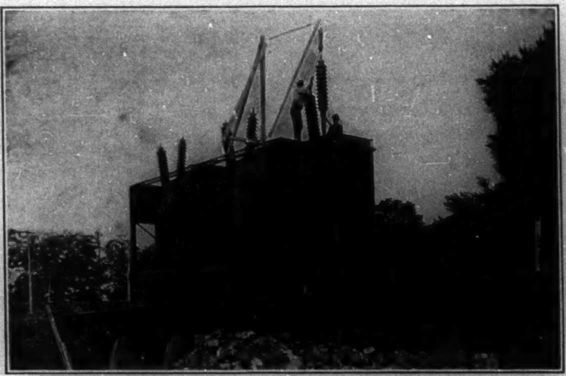
Auxiliary Transformer Windings. Small lead-covered leads are also brought out from the low-tension sides of the transformers from separate single-phase windings for 110 volts and of 10 kv-a. capacity each, which provide: first, current for the blower motor, regardless of what may be the high-tension or low-tension voltages of the main windings; second, lighting for the car; third, source of voltage for the instruments.

The Low-Tension Delta is established inside the switch cab shown on the right in Fig. 9, the leads being brought by the heavy lead-covered cables indicated, to a point near two switches, the far sides of which are connected together, and jointly feed the outgoing low-tension leads, which pass out of the rear wall of the switch-cab, through porcelain bushings let into a treated wooden terminal block, shielded from drip from the eaves.

Wiring and Switch Gear. High-tension wiring is bare copper. All low-tension wiring is lead-covered cable, the main leads being insulated for 13,200-volt operation, and of sufficient

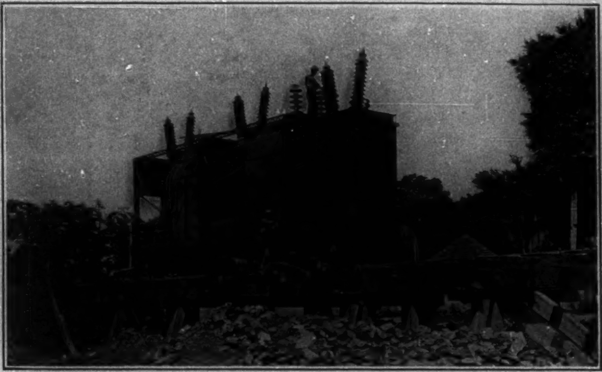
[BURKHOLDER & STAHL]

FIG. 5—CAR DISASSEMBLED FOR TRANSIT—SIDING AT KINGS MOUNTAIN, N. C.



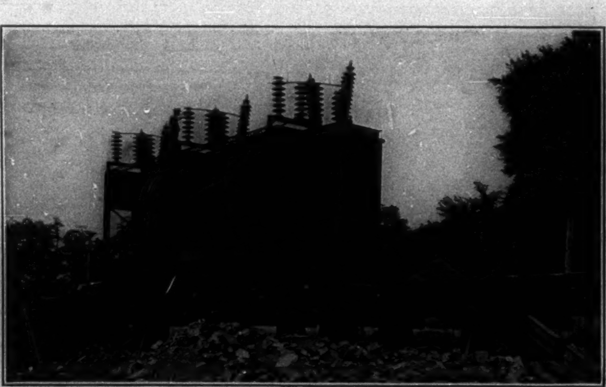
[BURKHOLDER & STAHL]

FIG. 6—CAR IN OPERATING LOCATION, KINGS MOUNTAIN, N. C. LOWERING TRANSFORMER TERMINALS



[BURKHOLDER & STAHL]

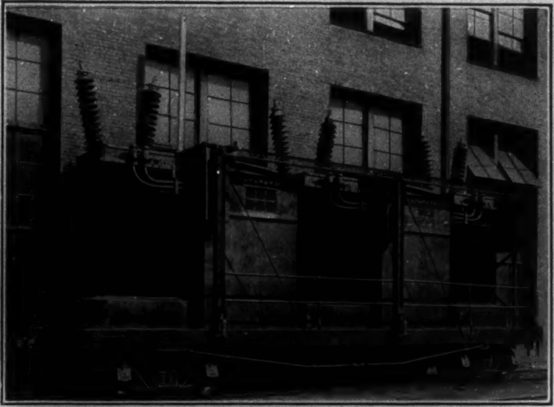
FIG. 7—HIGH-TENSION SWITCH RAISED INTO PLACE BY WINDLASSES



[BURKHOLDER & STAHL]

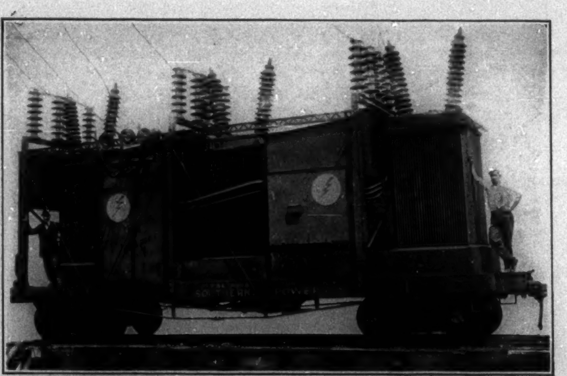
FIG. 8—HIGH-TENSION SWITCHES AND HORN GAPS ASSEMBLED

PLATE XII.
A. I. E. E.
VOL. XXXIV, 1915



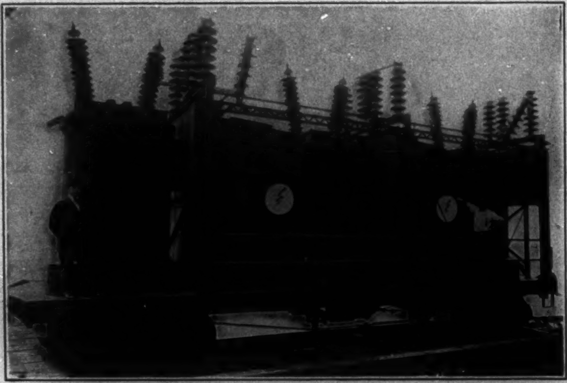
[BURKHOLDER & STAHL]

FIG. 9—VIEW OF CAB ENTRANCES AND LOW-TENSION WIRING



[BURKHOLDER & STAHL]

FIG. 10—SUBSTATION IN OPERATION ON 44,000-VOLT CIRCUIT



[BURKHOLDER & STAHL]

FIG. 11—SUBSTATION IN OPERATION AT HICKORY, N. C. (44,000 VOLTS)

capacity to carry full transformer output when operated at 2200 volts.

Suitable voltmeters, ammeters and watt-hour meters are mounted on an appropriate panel, also containing the operating handles for the low-tension oil switches.

In order to provide proper metering equipment for the lowest voltage (2200), as well as the highest, (13,200), of the low-tension arrangement, two sets of series transformers are used, and so operated from a pallet-switch, mounted on one of the oil switches, that when one of these switches is opened, the corresponding series transformers are short-circuited, and the series transformers for the other oil switch are connected to the metering devices. It was mainly to make "fool-proof" this part of the equipment that two interlocked low-tension switches were provided, both insulated for 13,200-volt operation, and one with adequate current-carrying capacity for full output at 2200 volts.

General Comments. The type of steel work selected affords ample mechanical rigidity for stability of operation and transport, and at the same time sufficient flexibility to withstand injury from the rough handling incident to switching operations on steam railroads.

No wood is used in the entire station, except for window sashes, and the outgoing low-tension terminal block.

Special attention was given to the accessibility of all parts and ease of removal in case of accidental damage, as well as to the protection of all parts that might be liable to malicious injury while the station was out of service. In addition to safeguarding the high-tension insulators for both transformers and switches, this includes such items as oil gages, thermometers, oil valves, blower intake, etc.

The total weight of the installation, including car, is approximately 135,000 lb., and the cost of such an installation, complete and ready to run, is approximately $21,000.00, or $7.00 per rated kv-a.

To place the equipment in service, it is first shipped by rail to the most convenient switch or siding, where proper high-tension voltage connections are made on the transformer terminal board reached through a hand-hole in the cover. The derrick is then erected and the high-tension terminals are raised out of the cabs, placed in the transformers and connected to the terminal boards. Then the horn gap switches are raised to position and connected to the operating rod, the delta insulators are hooked into place, connections are made between switches and transformer terminals, and the station is ready for connection to the lines. To provide additional room for operators, the racks which support the transformer terminals during transportation can be removed and placed at the back of each cab.

It should be noted that the station is self-contained and all parts of the equipment are transported on the car when in transit.

Figs. 5 to 8 show various stages in the process of putting the station into operation after its arrival on a siding at Kings Mountain, North Carolina, where it replaced a 3000-kv-a. substation undergoing reconstruction. Fig. 9 shows the entrances to the cabs, and Figs. 10 and 11 show the station in actual service at Hickory, North Carolina, connected to the 44,000-volt circuits, and carrying a load of approximately 1000 kv-a.

OPERATION

Although the main transformers are nominally rated at 1000 kv-a. each, test results show heat dissipation such that the station may have an output of 4000 kv-a. without exceeding standard temperature rise. On the same basis the permissible station capacity, without the blower, is easily 2000 kv-a.

The station was first put into commission at Kings Mountain, N. C., and was run there from July 12 until July 26, 1914, connected to the 44,000-volt transmission system, stepping down to 2200 volts, carrying an average load of 2200 kw., consisting of cotton mills and the city municipal lighting and power requirements. At this particular point the permanent substation had become outgrown and it became necessary to rewire and enlarge it. Instead of putting in temporary work, the portable substation was located on an adjacent railway siding and tapped to the main transmission line on the primary side. The various feeders from the permanent station were connected to an outside bus which was in turn connected to the low-tension terminals of the portable substation, thus cutting out the main substation entirely. This work was all done with practically no interruption of service to the city or the manufacturing interests, and permitted the work of rebuilding the permanent station to be done economically and expeditiously.

On the night of July 30th two of the three 44,000-volt transformers permanently installed in the substation at Hickory, N. C., failed during a lightning storm. The portable substation was immediately forwarded to this point and picked up the entire load of the permanent substation at 3.30 a.m. August 4th, and remained in operation until August 27th, carrying an average load of 1000 kw., consisting not only of cotton mill requirements, but also of municipal light and power requirements of the city. The permanent substation at this point is located about two miles from the nearest railroad siding. A 2300-volt circuit extended from the permanent station to the mill which was adjacent to this railroad siding. In order to pick up the total load of the permanent substation the top of the 2300-volt line was rebuilt so as to accommodate three 44,000-volt conductors, and the 44,000-volt line was extended over this line to the railway siding. The portable substation was then connected to this 44,000-volt line, and the 2300-volt circuit was used to transmit current back to the permanent substation and from there distribute it over the regular lines; the 2300-volt line being of comparatively small size, it was necessary to operate at a somewhat increased voltage in order to compensate for the line drop, and in order to take care of the mill immediately adjacent to the portable station two bucking transformers were installed, by which means the voltage for this mill was cut to the proper value.

On August 27, 1914, the substation supplying one of the mills in the vicinity of Winston-Salem was badly damaged by fire and the portable substation was immediately shipped to that point, and the service was restored at 3:30 p.m. on August 30th. The station remained in operation at this point from August 30th until October 18th, carrying an average load of 300 kilowatts. During this run the blower was not used. The supply mains to the mill were 13,200 volts primary and 2200 volts secondary. The portable substation was used in transforming these voltages.

When the station was taken out of service at Winston it was returned to Charlotte and a thorough examination was made not only of the apparatus of the station but also the car as well, and no defects of any nature were discovered.

No difficulties of operation were experienced, and, as a matter of fact, the operation was as reliable and satisfactory as that of the permanent stations would have been.

The station, in addition to the distance from Pittsburgh to Kings Mountain, has been shipped over about 275 miles of railroad in this territory, and no defects of any nature have become apparent.

The housing of the apparatus is of such nature as to make it unnecessary to provide any cover either when in or when out of service. A permanent place of storage has been provided for this station in the railroad yards at Charlotte. It is not necessary, however, that the station be stored where constant watchfulness can be exercised, as it is so well housed that it is practically impossible for anyone, so inclined, to meddle with it.

Notwithstanding the conflicting requirements of such a station, and the varied functions it is called upon to perform, the test of experience has demonstrated the adequacy of design, and yielded an operation eminently satisfactory.

DISCUSSION ON "A 100,000-VOLT PORTABLE SUBSTATION" (BURKHOLDER AND STAHL), NEW YORK, FEBRUARY 17, 1915.

K. C. Randall: Is there any provision for lightning protection?

Julian C. Smith: It is certainly a rather interesting development to think that the transmission system has provided this equipment for taking care of wrecks.

Why did the authors use three single-phase transformers? It would seem that for the purpose a three-phase transformer would be smaller and lighter, and all the purposes served by these transformers could have been accomplished by the three-phase transformer. It would have taken less space and could have been set down through the car, and possibly an oil switch might have been set on top of it.

L. W. Chubb: I ask the authors if there would have been any advantage in a higher enclosing wall so as to get a more direct draft along the corrugations.

Nicholas Stahl: The answer to Mr.Randall's query about the use of lightning arresters is a double one. In the first place, it was the purpose of Mr. Burkholder, as general manager of the Southern Power Company, to secure lightning protection from those substations in the vicinity of which the car would be located. The second part of the answer is found in saying that the length of the car was already considerably stretched for the weights it had to carry, and we were confronted with the difficulty of installing some form of arrester without oil; if we adopted the electrolytic type we were faced with the danger of slopping and spilling the oil, particularly so in heavy switching service, or transporting over the lines of the railroad.

Mr. Smith's question about the three single-phase or one three-phase transformer also received consideration, but it has been the practise of the Southern Power Company to make their installations with the single-phase type. And if they have any three-phase transformers on their lines at present I am not familiar with these installations. That is partly debatable ground with engineers the country over. But the question was raised and decided by the Southern Power Company.

As to the suggestion of locating the oil switch on top of the transformer—that would have been negatived in the Southland. We had to send the car over seven hundred miles of circuitous route, nearly double the usual distance, in order to get proper clearances. There are no tunnels which there impose such severe conditions, so that the statement with respect to the freedom of transit over these lines obtains.

Another reason is that the three-phase transformer would have involved us in difficulty unless we adopted oil switches with the transformer. There would have been no place convenient for locating the horn-gap switches. With the other switches we would have been liable to the same trouble of slopping oil.

In reply to Mr. Chubb, the initial proposition involved bringing up an outer partition wall substantially to the top of the transformer casing, and sending through that, by means of the subway, the air which is now liberated substantially from direct confinement at a height of 15 inches, approximately, above the car floor. Tests were made both with the anemometer and otherwise which showed that the air does hug the corrugations. So the outer partition wall was omitted for two reasons. First, it economized material and made a larger area-way for the trainmen to pass between the struts on the one side and the transformer case on the other. And it allowed a greater output for the station when the blower was not in service, on account of the greater radiation effect obtainable.

The squirrel-cage induction motor is fed from a low-voltage circuit in the main transformer and anything which occurred to disable it would put the transformers out of service also. It might happen that the blower or motor would be disabled, and in such case we would get through the self-cooling action of the tanks alone 50 per cent capacity of the station provided with the blower.

I might say again with reference to Mr. Smith's question about the three-phase transformer, that one of the points in mind was the ability to operate with 58 per cent of the capacity of the total in case one transformer was out of operation.

Addresses delivered at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 17, 1915.

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SYMPOSIUM ON "THE STATUS OF THE ENGINEER"

ADDRESS OF L. B. STILLWELL

IN ARRANGING the program for this evening the committee to whose efforts the presence of our distinguished guests is due gave consideration to the question whether it would be wise to attempt to suggest to the several speakers various more or less definite aspects or phases of our broad subject, with a view to avoiding repetition of thought and securing a comprehensive and systematic discussion. It was felt, however, that the most useful and constructive results might be expected if the gentlemen who are to follow me were simply invited to present for your attention those views and suggestions—based not only upon their exceptional experience as leaders in various departments of engineering accomplishment, but also upon their wide observation and experience as men of the world—which to them, severally, may appear of special interest and importance to the profession. If repetition results, emphasis will result, and the status of the engineer, as a professional man and as a citizen, can be systematically advanced only by that individual and that collective effort which it may be hoped will result from that conviction which follows the emphatic statement and reiteration of essential facts.

At the outstart, the expression "Status of the Engineer" appears to require definition. It may be interpreted to mean the standing of the engineer as it appears to his fellow citizens, or it may mean his standing as it would appear to an observer seeing facts as they are, without exaggeration, without diminution and without distortion. It is the well-known distinction between reputation and character. Reputation is the image of the man as he appears to those about him; character is the man himself. Not infrequently does it happen that the image bears little resemblance to the actual man. When this occurs the fault is sometimes that of the observer, but not less frequently, perhaps, it is the fault of the man himself.

Tonight, I take it, we are concerned with both aspects of our subject. What we may be able to do to make ourselves more competent as engineers, more useful as citizens, or better as men, is obviously of importance to every member of the engineering profession. What we may be able to do, by individual and by collective effort, to secure for the members of our profession that recognition by the public at large to which their character as men, their professional ability and their work as contributors to civilization and progress may justly entitle them, is also of obvious importance. Each of these broad aspects of the subject affords inviting opportunity for analysis and for useful suggestion along various lines of thought; but in introducing the discussion I shall make no attempt to treat the subject comprehensively, but shall endeavor to utilize the time which has been placed at my disposal by inviting your attention to certain opinions which I have formed, as the result of observation and experience, and submitting certain suggestions in regard especially to collective, or at least co-ordinated, policy and action by our great national engineering societies which in my judgment would tend from every point of view to improve the status of the engineer.

The opinion is widely prevalent throughout the ranks of the profession that the true status of the engineer is not recognized by those about him; that the work which he has done and is doing in the world entitles him to a larger place in the public view than he now occupies and to a larger share in the administrative work of the nation, state, local community, and of our great railway and industrial corporations than he now enjoys. Dealing with facts, as his scientific education and professional training have taught him to deal; trained in the solution of economic problems to exclude all that is irrelevant or immaterial and to deduce his conclusion by a process of exact reasoning from ascertained premises, he is amazed to observe a great economic question like, for example, the conservation of our water powers, involved in a fog of misunderstanding and misrepresentation so dense that neither the public nor our lawmaking authorities can be expected to see it in its true proportions. Knowing, as he does, that no education leads with greater certainty than that of the scientist and the engineer to the formation of sound opinions and well-grounded, conservative judgment, and believing, as he does, that the ranks of no other profession include a larger proportion of men of clear view, broad intellectual comprehension, unblemished character and executive force than are found among the members of our national engineering societies, he finds it difficult to understand why the appointment of an engineer as a member of one of the many commissions of investigation and of administration, to which in these days the functions of government in this country are increasingly confided, is a phenomenon of extremely rare occurrence. His conclusion generally is that these are matters for the politician, not for the man trained to view facts in their true light, unwilling to misrepresent or mislead the public for political effect or to seek preferment by following the usual well-worn paths; and too often he follows up this conclusion by burying himself in his scientific studies or professional activities. Such a decision can be in no way justified. As a citizen trained to see true, to think straight, possessed of special knowledge regarding many of the great economic problems of our time and conscious of ability to deal with them effectively, it is the duty of the engineer to assert himself as a citizen. Recognition in time will overtake and keep pace with achievement if we do our part, not only as men of specialized training, but also as men of the world and as citizens who, by reason of that very specialized training and experience, owe in a peculiar sense a duty to the community, in these days of vast and complex economic and social problems, which in themselves are a result of the work of the applied scientist within comparatively recent years. The engineer who buries himself in the technique of his profession cannot justly complain if he fails to attain a position as a leader of men. Like Franklin, he must at times leave the laboratory of science for the forum of discussion and the hall of legislation, if he would fulfill his duty as a citizen and secure that recognition of his intrinsic ability which he desires and to which he is entitled.

In his scholarly address delivered at Ottawa on June 18, 1913, Dr. George F. Swain, president of the American Society of Civil Engineers, brought to the attention of the oldest of our national engineering societies many facts which are of profound interest to all professional engineers. His discussion is philosophical in thought, felicitous in expression and singularly convincing in its reasoning. It should be read and then read again by every man who is, or aspires to be, an engineer. His subject was: "Some Tendencies and Problems of the Present Day and the Relation of the Engineer Thereto." Neither the present status of the engineer nor the responsibilities which in a peculiar sense devolve upon him in these days of vastly accelerated economic progress can be realized clearly without an examination of these tendencies and problems. It would be difficult, if not impossible, for any man to improve the admirable discussion of the subject which Dr. Swain has given to the profession in the paper referred to, and I earnestly hope that every engineer present this evening will secure a copy, will read it carefully and thoughtfully, and then will do what he can to oppose and correct the unfavorable phenomena of our time to which Dr. Swain calls our attention. The time at my disposal does not permit even a résumé of these phenomena, and I pass, therefore, to the question, "How may the status of the engineer be improved?" However we may differ in our views of what his present status is, we are unanimous in the desire to see that status advanced. The practical question which interests us is, what can we do to secure this advancement; what can we do, by individual and by collective effort, to make the engineer still more effective in his professional work and more useful as a citizen, and to secure for him more general and more definite recognition by the community at large?

Obviously, there are several lines along which intelligent and systematic work may be expected to promote the attainment of these objects. While recognition may lag behind achievement, we may nevertheless rest assured that every advance in the character of the engineer and in his ability to perform his work effectively will be followed by increased recognition of his position as a man and as a professional worker in the community. In this connection, next to integrity of character, education is of fundamental importance. In our schools and colleges the aim should be to train the mind rather than to impart technical information. The curricula of our technical schools differ so widely that safe generalization is difficult, but in my opinion the tendency should be toward a decrease in the time allotted to technology and an increase in that allotted to certain of those subjects which comprehensively are grouped under the name "humanities." It is greatly to be hoped that the time may come when no American institution of learning will confer an engineering degree except upon a student who has completed a four-year course in arts or philosophy and a two-year course of technical instruction in the department which he may select. It is not essential perhaps that the engineer should have studied Greek, but in my opinion no degree in engineering should be granted to a man who has not studied, for example, logic, rhetoric and political economy, as well as mathematics and the essential branches of pure and applied science which in his education have particular reference to his specialty.

Moreover, a man's education is not completed when he receives his degree at graduation. It would be as true, perhaps, to say that it begins at that time; and, without attempting to discuss the subject at length, I may be permitted to suggest that the average engineer, ten years or twenty years or thirty years after graduation, will be not only more interesting to himself and to his friends, but will be also a more effective engineer, if he has not confined his attention exclusively to his special line of practise but has availed himself of the many opportunities which occur in life to broaden his horizon and to add to his store of knowledge in departments of intellectual activity other than that which he has made peculiarly his own.

Primarily each engineer must make of himself what his ability and opportunities may permit. This, and this alone, can fix his professional character—his true status. But, while character is far more important than reputation, reputation also has its value, and a correct appraisal of the engineer by the community at large is to be desired, not only because of its effect upon the engineer himself, but also, and more especially, because of the vastly increased utilization of the engineer's abilities in the service of the community which would result.

It requires no argument to show that the community at large cannot be expected to appraise correctly the capabilities of the engineer if the latter adopts and systematically pursues throughout his career a policy of total abstinence from every form of indulgence in public affairs. I have already touched upon this point briefly, and I trust that it will be developed and emphasized by other speakers this evening, some of whom, by example as well as by precept, have illustrated and taught this doctrine in a manner which already has done much to demonstrate to the American public the fact that the same kind of brains which the investor selects to solve a complex problem of engineering construction, or to find gold where others cannot see it, can be relied upon to find the answer to a complex economic problem requiring legislation, or to point out an essential principle which has been concealed by a mass of irrelevant rubbish.

Our national engineering societies can do much to secure for the engineering profession the recognition to which the character and the achievements of its members justly entitle it. For years they have been doing splendid work in the post-graduate education and training of their members, by affording opportunity for the presentation, discussion and dissemination of technical information, but as yet have they failed to establish for the profession a standing in public estimation comparable, for example, to that of the legal profession.

Let us consider briefly certain measures, apparently within the power of our engineering societies to adopt and enforce, which if adopted would tend to correct this situation.

Our engineering societies can do much by the exercise of unceasing vigilance in preventing the admission to our ranks of unworthy or unqualified applicants. In the absence of any system of federal or state license under which the professional engineer may qualify and practise, even that part of the public which may attempt to exercise intelligent discrimination can base its opinion of the qualification or lack of qualification of the engineer only upon the fact of membership or non-membership in one or more of the great national engineering societies. And what have these national engineering societies done to define and establish the professional standing of their respective members? Without undertaking to answer this question specifically, it is probably fair to say that, as regards at least two of these societies, the requirements for admission and the scrutiny and selection of new members are all that can be expected and possibly that could be desired. Some of the societies, however, apparently might " stiffen " their requirements for admission, to the advantage of the entire profession, and might draw more distinctly perhaps the lines which segregate the members into several classes or grades which are supposed to correspond with more or less accuracy to the comparative professional qualifications of those who compose them. Nevertheless, it is a fact, I believe, that membership in a national engineering society today means more than it did twenty years ago and that the state, municipality, corporation or individual seeking to employ an engineer is less likely now than then to select one who has not been recognized by his professional brethren as worthy of membership. But, aside from the advantage which would result from bringing the requirements for membership in all of these societies up to the level of those which have adopted the most advanced standards, there are several important steps which the national societies might take which undoubtedly would contribute materially to the advancement of the status of the profession.

(1) Several of our national societies have adopted so-called "codes of ethics" or rules of practise. Many of these rules involve no questions of ethics. They are rules deemed by the respective societies useful to their members in their professional practise, and their enforcement or non-enforcement has no particular bearing upon the status of the engineering profession as viewed by the public.

In so far as ethical principles are involved, however, whether a code be adopted or not, there can be no question that the adoption and enforcement of rules which would result in the prompt expulsion of any member proved guilty of dishonest practise would do much to increase general respect for the profession. Up to the present time our societies have signally failed to establish their position in public confidence by disciplining members even in flagrant cases. At a comparatively recent meeting of the American Institute of Consulting Engineers, a distinguished member of that organization and of the American Society of Civil Engineers made the statement that an examination of the records of three of the great national engineering societies failed to disclose a single instance in which a member had been expelled for violation of the ethics of the profession. Even in certain cases where a member of the society has been convicted by the courts, the society has failed to expel and has allowed the member to resign. I am aware of the responsibility which a society may assume in branding a member by expelling him, but until the societies have the wisdom to so amend their rules as to provide for expulsion in flagrant cases and the courage to expel, they cannot expect the public to accept the fact of membership as in any sense a guarantee of professional honor. Surely the establishment and enforcement of regulations which would result in the prompt expulsion of a dishonest member is a step which each of our engineering societies can take. To the great credit of the profession, it may safely be said that the number of instances in which such action might be justified and necessary would not be great. The effect of a few salutary punishments of this kind would be far reaching and might be confidently expected to improve the standing of the society in the eyes of the public. Our friends the lawyers have long recognized the necessity of fortifying the status of their profession by providing, through the medium of their bar associations, for the trial and expulsion of members who may violate the ethics of their profession. How strictly this rule is enforced I cannot say, but it is evident that even the occasional enforcement of the rule must contribute effectively to the establishment of the public standing of the profession.

In my opinion, no society by a single act could do more to advance the status of the engineering profession than could be accomplished by conspicuously expelling any member found guilty of dishonesty in the practise of his profession.

(2) Perhaps the most encouraging evidence that our national engineering societies are coming to recognize the fact that cooperation in matters of common interest is essential to the well-being of the profession, is to be found in the action recently taken by six of these societies, through the appointment of a joint committee which has agreed upon a bill for licensing engineers which has been submitted to the governing bodies of the several societies. It is earnestly to be hoped that the governing bodies of these societies will lose no time in bringing their best judgment to bear upon this extremely important question and, having reached a decision, will take effective action to safeguard and promote the best interests of the profession.

(3) The national engineering societies can advance the status of the profession by exerting themselves to direct public policy in economic questions along sound lines of development. I have not informed myself recently in regard to the policy and action of other societies, but for several years past the American Institute of Electrical Engineers, from time to time, has sent committees of specially qualified experts appointed from its membership to appear before various heads of departments at Washington, or before committees of Congress, in relation to such questions of fundamental economic importance to the country as, for example, the utilization of water powers on the public domain and in navigable streams. These committees have discussed only the engineering and economic aspects of the questions under consideration. They have been careful to avoid all political or legal questions. Their reception in every instance thus far has been not only respectful but courteous, and it is believed that the information which they have been able to convey has been useful to the authorities. The members of the several committees have paid their own expenses. They have rendered this service because they have realized that legislation

permitting, for example, the control and development of water powers upon sound economic lines is of very great importance, not only to those members of the engineering profession whose activities are concerned with hydraulic or hydroelectric development, but to the country, at large. Along such lines as these, there is no valid reason, in my opinion, why all of our great national engineering societies should not co-operate in placing at the disposal of our national legislative and executive authorities, from time to time, the special knowledge which is possessed by their representative members and which the authorities must have if mistakes that may result in great harm to the economic interests of the country are to be avoided.

ADDRESS OF E. W. RICE, JR.

THE SUBJECT for discussion this evening is important and timely, and should be of vital interest to every engineer.

It is well for us to pause a few moments from our daily task and make a brief survey of the engineer's work, to consider its important influence upon the life of this busy world, and especially to enquire what new service awaits the engineer now and in the immediate future.

During this discussion we do not propose to limit our definition of "engineer" to one educated in or following the strictly technical profession of civil, mechanical and electrical engineering, but shall include in addition all educated men laboring in the broad fields of chemistry, physics, medicine and other organized scientific activities.

I do not think that we can be accused of serious exaggeration in saying that the world is indebted to such men for the application of steam to ships, cars and workshops; for the invention of the sewing machine, the typewriter and the phonograph; for the introduction of the bicycle, automobile and aeroplane; they have brought the marvels of photography into existence, giving us the moving picture, X-rays and colored photographs. High explosives have been created to build and to destroy. We must thank such men for the untold blessings of anesthetics; for showing us how to successfully limit and combat epidemics of dread diseases.

Coming to our own special field, the members of our profession have given the world the telegraph, the ocean cable, the telephone and the wireless; created electric lights for our homes, cities and workshops; the electric motor to run our trolley cars, railroads and factories; have designed dynamos and great transmission lines with which to save and make useful the otherwise wasted power of our waterfalls. These and many other contributions equally wonderful and equally useful—miracles at first but now mere commonplaces and necessities—have been evolved from the brains of our busy scientific engineers largely during the past 40 years.

But I will not weary you with a further recital of engineering achievements, as such a recitation of even the shortest possible catalog would consume the entire evening.

My object in thus calling attention to the relatively recent contributions of engineers to the wealth and resources of the world is not to tickle your pride in belonging to the engineering profession, but rather to awaken your sense of responsibility for the great changes in our daily life, our methods and opportunities of conducting business and all other activities, which have been brought about directly and indirectly by such accomplishments, and to make some suggestion for the meeting of this responsibility.

Is it not a fact that civilization in its present form would never have arisen and would speedily come to an end if deprived of the engineer and his services? Has not the equilibrium of the world been upset by these very gifts of the engineer?

Is it not evident that such tremendous additions to our power, knowledge and wealth must have a powerful influence upon every phase of our existence? Have not our relations with nature and with each other been profoundly affected, and as a result required many new adjustments?

The discovery of new trade routes has, as is well known, completely changed in times past the history of nations and the fate of their peoples. The discoveries of our scientific engineers during the past 40 years have been of greater importance than discoveries in trade routes, and it is inevitable that in adapting itself to the new conditions society should be deeply affected. The adaptation of man to his new environment could not take place without strain and friction. Are we not now in the midst of such a process of adjustment?

Of course, we all appreciate that the labor and thought of many other men of vision and enthusiasm were needed; men experienced in finance, commerce, trade and government, to render the all-essential aid required to introduce and to adapt to our daily lives these great contributions. But it would seem to be self-evident that without the creative work of the scientific and technical engineers these things would not have seen the light of day.

This remarkable development was fairly started during the first half of the 19th century under the guidance of the civil, mechanical and chemical engineer, but was tremendously accelerated by the advent of the electrical engineer about 40 years ago. His work during the past decades has reacted upon that of the other engineering professions and stimulated and made possible the almost equally marvelous development in mechanical, chemical and other lines of activity. Therefore, I regard all those who have been able to participate in the service of electrical science as happy and fortunate individuals. It is true that financial reward has not always been great; on the contrary, it has often been extremely meager when compared with the rewards which frequently come to the successful lawyer, financier or merchant, but our engineer has been rewarded by something more valuable and precious than gold—the thrilling joy of achievement. There can be no greater satisfaction than that which comes to a man who believes that he is the first to discover some new force or to make some new and useful invention.

I have lived with and worked alongside of engineers more than 30 years. I think I understand the engineer's aspirations and character. I can say that it is a case where familiarity has not bred contempt, but, on the contrary, has inspired respect and affection.

The engineer is popularly supposed to lack certain qualities needed in a successful man of business, or to make a good salesman, or to handle important financial matters, or to fill positions requiring general executive ability. Is this popular idea justified? We may admit that an engineer who has devoted his entire time to his exacting work may be lacking in the knowledge and experience of other lines of activity, but it does not prevent him from having certain natural qualities, integrity, tact and aggressiveness combined with general intelligence and common sense. These qualities are personal and not professional. No group of men has a monopoly of such qualities and in none are they entirely lacking. These qualities are to be found as generally among engineers as among other men.

It has been further charged that as an engineer deals with nature and natural laws his experience has been limited to impersonal objects, and that he must fail to appreciate or understand the complicated human element which is the important factor in business or in political life. This may be also partially true, particularly in the case of some of those whose work has been confined to that of pure research or pure science, but is not a general condition even among such men, and by no means the condition among engineers who of necessity are brought more or less in contact with the human element.

I have noticed that an engineering education and training have generally developed a man's powers of observation and his desire and ability to learn. He becomes skeptical of mere theories, doubts tradition and spurns superstition, but he constantly searches for the truth and is not afraid of facts. He habitually tries to see things as they are and not as he thinks they should be. He is never satisfied that "whatever is is right," but is ever trying for something better. I do not need to tell this audience that engineers do not always agree as to the interpretation of facts, but opinion is frankly based upon facts and not upon preconceived notions. One who refuses to face or acknowledge facts loses his influence upon his fellows and his standing among his brother engineers. The engineer is always "from Missouri."

There is an old proverb which runs somewhat as follows: "One look is worth a thousand words." I like that proverb, and it is, I think, a fair description of an engineer's point of view. How often you hear the expression among engineers—"Well, let's go and take a look at it." Is not this the spirit which is needed in respect to other problems in the social, industrial and political world? Do they not need less talking about and more intelligent looking at?

It is true that the engineer deals primarily with nature, but nature does not lie. The engineer, therefore, learns early in life the utter uselessness and folly of deceit. He knows that it would be silly to the point of insanity to try to fool nature. He is constantly on his guard not to fool himself and is therefore not likely to try to fool others. In fact, he loses in time the desire to deceive, even if he ever had it. Honesty becomes a habit, not the honesty of the old-line trader formulated in the saying, "Let the buyer beware," but the kind of honesty which scorns to take advantage of the negligence or ignorance of his customer, which involves honest thinking as well as honest action. It is quite possible that this habit may make him at first the easy prey of dishonest men, but it is a quality which commands respect and which wins in the end. It is needed and appreciated in business of all kinds and sizes, little and big. It is helpful to little business. But big business is doomed to big and disastrous failure unless saturated with honesty.

The engineer's training also tends to produce in him a fine blend of conservatism and radicalism. He is not afraid of a thing because it is new and he is not slavishly bound to precedent; on the contrary, he is frequently the creator of new things and a breaker of precedent, but he also believes in continuity and is not likely to let go of the old until he has a good hold of the new. He does not adopt an idea merely because of its novelty, but demands before adoption, the acid test that it should be really better than the old.

There is, therefore, a large field of service open to the engineer in manufacturing, commerce, farming and all other business activities of our country for which his education and training have made him eminently fit. In fact, his work in science and engineering, already briefly alluded to, has succeeded in so increasing the magnitude, variety and intricacy of manufacture and trade that the special knowledge of the trained engineer is already in demand in almost all departments of our commercial and business life. Even in the specialized field of selling, the old type of salesman with precious little technical knowledge has been largely displaced by the engineer salesman.

There is, however, another opportunity for service awaiting the engineer of a most valuable and patriotic character. The biggest business, after all, is that of running this great country of ours. The United States not only operates the largest businesses itself in its various departmental activities, but through its legislators and various commissions it has taken a lively and paternal interest in private business. It makes the rules for the conduct of our business which fundamentally affect our future for good or for evil. It seems to me that the engineer ought to take an important part not only in conducting this great enterprise but in helping to make the rules for our faith and conduct.

I recently heard a member of Congress say that in looking in

Congress one was merely seeing as if reflected in a mirror the great people who elected it, and that if we, the people, did not like the looks of ourselves we should not get angry and break the mirror but go and wash our faces. Now, while that was a very humorous and witty simile it seemed also to convey a homely truth and a sensible suggestion. I began to wonder how much there was in the suggestion, and thought I would ascertain just how accurate a reflection of our people and its activities was to be found in Congress and Legislature. I thought it would be interesting to learn the profession or vocation of those whom we have elected to represent us in Congress. I have here a list from which I will briefly abstract:

1914.

SENATE OF U. S.

	Number
Lawyers	71
Farming	5
Banking	4
Publishing	4
Merchants, mfrs., railroads, real estate	7
U. S. Navy	1
Medical profession	1
Not specified	3
Total	96

HOUSE OF REPRESENTATIVES

	Number
Lawyers	275
Editors and publishers	23
Merchants & manufacturers	32
Other business	32
Farming	14
Banking	4
Educational profession	6
Medical profession	5
Architects	3
Engineers	1
Not specified	40
Total	435

It will be noted that 75 per cent of the senators are classified as lawyers, and 65 per cent in the House come under the same classification. I may say, incidentally, that I did not find a single one among the senators who professed to be an engineer, and only one in the House of Representatives. An examination of the roster of the State of New York shows a similar condition, a large majority of the membership of both the Senate and Assembly being classified as lawyers. Now, I do not know how these facts impress you, but the witty simile of which I spoke rather lost its point as a conveyer of homely truth in the light of the facts. A body whose composition is about 70 per cent lawyers cannot be considered as a very accurate reflection of the people of this country. Now, I have the utmost respect for members of the legal profession. We are all constantly trusting lawyers with our most important business matters and intimate private affairs. No profession has higher ideals and no profession comes nearer to realizing these ideals in practise. They deserve our confidence. I also yield to no one in my admiration of the ability, integrity and patriotism of the great men whose names have honored the legal profession and shed luster upon our country; men who frequently at great personal sacrifice have given the best part of their lives to the service of their country.

However, I think it is competent for us to enquire as to whether there is not a disproportionate number of members of the legal profession in our law-making bodies. Is it for the best interests of this country to have any one kind of talent and training or point of view so overwhelmingly represented? There is a pretty general opinion in this country that we are afflicted with too large a number of laws, and it has been suggested that there may be a connection between the number of laws and the number of lawyers in our legislative bodies. Is it not also a strange anomaly that a country which owes so much of its phenomenal prosperity to the creative work of engineers should have practically excluded such men from its Congress and Legislatures? Would not our general condition have been better if years ago we could have injected into the composition of our law-making bodies a number of high-class, sensible engineers? It seems to me that our engineers have a duty to perform, that they owe it to themselves and to the country not to be satisfied with being simply hired to give their views and professional opinion upon programs prepared by other men, but should sit with our rulers and share directly in the responsibilities of government.

It is reasonable to expect that men who have been the greatest factor in the creation and conservation of our material wealth and resources should have sound and constructive ideas of practical value upon the matters which our commissions are created to control. Therefore, our great commissions which are charged with such tremendous power and grave responsibilities should have among their members competent engineers of experience as well as lawyers, practical business men and experts in the special province over which the commission has jurisdiction.

One of the most hopeful signs of the times is the great awakening of the business men of this country to the imperative necessity of taking an intelligent interest in our government, and it looks as if our business men now propose to make a business of seeing to it that they are properly represented in the business of government. Engineers should arouse themselves and participate in this great movement.

While up to the present no better or more practical means has been discovered than our great political organizations for giving effect to the wishes of our citizens, it is becoming increasingly evident to thinking men that no permanent advance can be made by simply turning out one political party and substituting representatives of another as our rulers. An intelligent and continuous effort should be made to improve the composition of our legislative bodies. We are essentially a nation of manufacturers, traders and farmers. We are all part of an organization with a mechanism which is so delicate, extensive and complicated that it must be controlled and managed with the greatest wisdom and intelligence if we wish to continue to progress in prosperity and lead happy and useful lives. It seems to me that in the future it will be the duty as well as the privilege of the engineer, who so largely contributed to the production of this complicated mechanism, to assist in its management in order to assure its preservation.

ADDRESS OF E. M. HERR

THIS TOPIC is now so wide that there is no difficulty in discussing it from one's own particular point of view and in line with any individual interest and experience. The danger lies in dealing with so broad a subject from too limited and narrow a point of observation. It is doubtless from a full realization of this danger that those responsible for the program tonight have brought men together in this discussion from so many different positions and varied experiences in life.

Having announced my apprehension regarding the narrow view of this broad question, I feel at perfect liberty to proceed to take such view, if only to make good my prediction.

My experience for the past eighteen years has been with the engineer in manufacturing business and the last ten years in a business so highly technical in its character and developing so rapidly, largely through the efforts of these very engineers, whose status we are here to discuss, that it was often a question whether we were engaged in engineering our manufacturing or manufacturing our engineering. As fast as the factory learned how to make a machine or device of any kind, the engineers would bring out an improved design and the shop had to begin all over again and learn anew the lesson which had cost so much in time, effort and material. At such a time one sympathizes with the self-made railroad superintendent of my acquaintance in Chicago, who, after receiving notice from the chief engineer of the railroad that such and such changes must be made or limitations put upon speed of trains or weights of engines, would frequently say: " If we could gather up all the engineers and drop them in the middle of the lake, we could make some money for our stockholders." And so he might have done for a time, but from this remark it is evident this superintendent was desirous of standing still as to progress and improvements. Here we have one answer to the question under discussion, viz.: The engineer stands for progress and improvements. Progress and improvements! What a fine status for any profession. If the engineer always stands for genuine progress and real improvements can much more be desired? Let me therefore counsel our young engineers to adopt this as their slogan, and always be sure, in their engineering reports and recommendations, that they stand for progress and improvements that are both genuine and real.

The engineer is not restricted in his sphere to dealing with inanimate things, broad as is the field of improvement and development of the materials, processes and products of a business.

It was an engineer who first developed the principles of scientific management, and the men who have brought the greatest contributions to the wonderful advance in the handling of workmen, resulting in materially increasing their efficiency without adding to but often lessening the drudgery of their work, have all been engineers.

Engineering, originally the art of managing engines, was later defined as "The art and science by which the mechanical properties of matter are made useful to man in structures and machines." This definition is now far too restrictive and must hereafter include men as well as materials; animate as well as inanimate matter.

In the management of men, the engineer, as usually trained, has his severest test. Many engineers, remarkable for their judgment, skill and intelligence, fail dismally in handling men.

The very nature of the training of the engineer tends to unfit him in directing and controlling the rank and file of the workmen. The exact and uncompromising methods so necessary in engineering training cannot be applied in dealing with men. Fairness and justice are the cardinal principles to be used always, but in addition, in dealing with people one must know how to bring the human element into all such relations. When this is properly done, the workman is inspired, stimulated and led into obedience and loyalty to which no severity or rigid rules could drive him.

It might be thought that training and directing workmen is not part of an engineer's work. Formerly this was true, but with the rapid growth in the technical requirements of many kinds of manufacturing, and the development of improved methods of management of shop work, the latter devised and developed by engineers on engineering principles, the old rule of thumb methods of shop management are fast becoming obsolete and either the old men must learn the new methods or our young men with engineering training must learn how to handle men skilfully and fairly.

Another field rapidly opening to trained engineers is the commercial one. The product of many of our factories is so technical, from an engineering standpoint, that only an engineer trained in that specialty can properly present it to prospective customers.

It is, therefore, seen that not only does engineering include, besides the designing and constructing field, the managerial and executive work which also demands this trained intelligence, but even the salesman, who is popularly supposed to be born, not made, is leaning heavily upon the engineering profession. This can only point to one conclusion: In the manufacturing business, the engineer, formerly useful for designs and specifications, is becoming necessary in practically all branches.

The daily increase in the complexity of our civilization inevitably increases our industrial development, and as we have seen, consequently extends and broadens the field of engineering work. Can we wonder then at the enormous increase in the attendance at schools of engineering and the rapid strides made by our engineering departments in the university as compared with those of the academic departments?

It is naturally rather stimulating to our pride as engineers to contemplate the rapidly widening field which the profession is occupying, but we must not forget that with this broader field comes greater responsibility and the necessity for more careful and thorough training than in the older times of simpler conditions.

But, it will be said, while our activities and responsibilities are greater, so also are our resources; and does not the multitude of improved processes, labor-saving devices and space and time savers, such as the many kinds of rapid transit, the telephone, telegraph, etc., more than make up for the difference?

In some parts of engineering doubtless this is true, but in what I will call the newest branch, viz., the engineering which deals largely with men and not with machines, the managerial and executive work to which the profession is being called with rapidly increasing urgency, but little help is found in new inventions. In this new field (if such it can be called) the ability to analyze accurately and draw correct conclusions from clearly perceived premises, so essential in general engineering, is just as important.

The difficulty which most engineers find comes from the analysis of cause and effect in the management of and dealing with men and women instead of machines or structures. The former is more difficult as a problem and was formerly only solved by those thought to be specially gifted in their ability to handle men. Like many other so-called "gifts," this one can be learned, not by inflexibility and severity, nor, on the other hand, by weakness and vacillation, but by even-handed justice tempered with humanity.

No fair man wants more than justice and I maintain that very nearly all men are fair or want to be. The difficulty comes in knowing how to deal justly and humanely in every case, and in the pressure and urgency under which business must now be done. He is both patient and wise to a remarkable degree, who can attain unto it.

Is not, however, the man with an engineering training far better equipped for weighing correctly the elements which must enter into such a decision? He is, with but one exception. This exception is his training and tendency to analyze mathematically. The very training in mathematical analysis, so largely a part of an engineer's education, to a considerable extent unfits him for a correct weighing of what I have called the "human element."

As an illustration, there is a great difference in the effect upon an employee of the way an order or decision is given. You all have probably at some time dealt with those in authority, from whom you would rather receive a refusal than an acquiescence from another. An adverse decision would be received from the former superior and carried out with a feeling of loyalty and willingness, but with an unavoidable feeling of grudging obedience and almost revolt from the latter. The different effect upon the employee was caused by the employer's knowledge of and due regard for one phase of the human element in dealing with the employee.

Many other conditions, largely personal in their character, must also be considered and given due weight in an analysis embracing the actions of men and women.

This is the element to which I wish especially to direct the attention of the young men of the profession. That it can be learned, I know from my own experience, which also has taught me its value.

Keep steadily in mind the Golden Rule—Do to others as you would have others do to you—and your judgment, with this in mind, while not susceptible of mathematical proof, will not fail of at least some part of the human element and ring true to the requirements.

Do not misunderstand me to advocate a departure from engineering principles in this matter of dealing with men. On the contrary, they must be dealt with logically and correctly, and a proper application of the principles of good engineering can bring only this result. No correct result can be obtained in any engineering or other problem if any of the elements are left out in its analysis. The human element is a factor and must be included or your result is not true. Therefore, I repeat that the engineer is needed in the shop and other places where men, and women too, must be managed and controlled. In this work his status is broadened and his influence greatly increased, but more important still, the engineer himself is made a more liberal, broader, better and more useful member of society.

Such an engineer will have a broad perspective, because he is accustomed to observe tendencies in both men and affairs and to draw correct conclusions from them. He can lay plans far ahead and, seeing clearly the ultimate result, is able to take full advantage of the tendencies in both his own field and that of allied lines of engineering, not only foreseeing demands but so shaping his activities as to create them.

ADDRESS OF ALEXANDER C. HUMPHREYS

I FIND that I am somewhat at a disadvantage in this symposium, and it is my own fault. I have had the opportunity to prepare an address for the occasion, but I have tried to listen attentively to those who have spoken ahead of me, and I shall try to get my text from what they have said.

I quite agree with the speakers who have preceded me in thinking that there is no reason to dread repetition. There is plenty of room for emphasis in anything we have to say on an engineering subject, or any other subject, for my experience is that in anything we are trying to show to others, or to convince others they should agree with us on certain propositions, we make but little progress anyway. There is a large amount of paraphrasing to be done, and sometimes the discussion and the emphasis lead us to correct our own views.

I think I should first want to lay stress upon the suggestion which has been made by Mr. Stillwell, as to the influence of character. Much is said about the education of the engineer, and especially the education of the engineer in college, yet, after all, the student is not prepared to take his place in the engineering profession unless that question of character assumes its right place. In fact, the more brilliant a man is as an engineer, the worse citizen he may be, if that question of character has not its proper place.

It seems to me that in much of our work in our Institute this question of emphasis might be brought out, because we, I think, bring forth a great mass of undigested material. It is not properly or fully discussed, and the result is our proceedings are filled with undigested material, some of which should be emphatically contradicted. On the other hand, there is much material that should be emphasized and re-emphasized, and therefore I want again to second Mr. Stillwell, this time with regard to that address of Prof. Swain's. I think we could all afford to read that at least once a month, just as I think we could all afford to read Prof. Rankine's dissertation which is a sort of introduction to his "Mechanics." I am debating whether I shall not make it a condition of graduation at Stevens that no senior shall graduate unless he can pass an examination on Rankine's dissertation. I wonder how many in this room have read it?

Of course, it would not look well for all of us to get up here and agree with each other on every point. I always find it agreeable to agree with everybody who speaks at the same time I speak, but I am not going to agree with Mr. Stillwell with regard to his suggestion of a six-year course in engineering. Dr. Swain, I saw right off, knew I was not going to agree with Mr. Stillwell, and I believe Dr. Swain does not agree with him either. We may agree, however, more nearly than would appear on the surface. I do believe absolutely with Mr. Stillwell that we should not so confine our education for engineers in the college as to have them limited to technical studies. On the contrary, I am a strong advocate of a more liberal course. But I do not believe that the college is the only educational agency. Far from it. If it were, then we would have a very poor lot of engineers.

I do not want to be misunderstood. I do not think that the college is actually *necessary* for the brilliant man, or the man who can work 26 hours out of every 24, to get his education. It is the best preliminary training, in my opinion, for the average man, but I do not care who he is that goes to college, if he depends on that education he will never be an engineer in the true sense of the word. He must still graduate from the school of experience. My point about the four-year course, the two-year course, preliminary to the four-year course, or the six-year course, is that the argument is generally made, as far as I have heard it, that we need to increase the length of the college course in engineering to keep abreast with the progress of engineering science. Then how many years shall we increase it, if we are going to cover the field? Will two years more do it, or four years, or six years, eight years, or ten years, or shall we keep a man in college until he is seventy years of age? He will not keep up with the progress of engineering science even then. In other words, while the man must be trained broadly in the fundamentals of engineering science, yet the practical engineer to be efficient must be a specialist, and the sooner he gets out, after he has learned the fundamentals, the more quickly and more efficiently he will acquire his training as a specialist. That is my opinion, based on my observation before and since I have been president of Stevens Institute of Technology. On the other hand, I believe today in America we are distinctly at fault, for the boys come to us at college at eighteen years of age, knowing far less than they ought to know, and this because they have been crowded through so many subjects that, as a class, they are not thorough. I believe that our public schools and preparatory schools generally can do more than they are doing if we could only recognize what is the truth, and recognize what is not the truth, with regard to education. Thoroughness in the fundamentals should be the basis for all education, and failure here is not compensated for by a smattering of many subjects.

It seems to me that in considering the status of the engineer today there is a broad responsibility to be considered. And I believe, based on a rather wide experience in engineering and outside of engineering, the problems to be settled in this country today, if this country is to continue in prosperity and not to have practically a revolution, are many of them, if not a majority, connected with engineering and the industries. If that be the case, what particular training should be peculiarly valuable in the settlement of these problems? Certainly the men who are trained in engineering and industrial management. But still, as has been pointed out to you by the last speaker, it is the engineer and the industrial worker who is least considered today with regard to law-making and the settlement of these problems. It is very interesting to be told the proportions of the different professions represented in our Congress. For instance, 75 per cent of the membership, as we have been told, is represented by the legal profession. There is only one engineer. I notice, however, with a good deal of interest, that there are two undertakers in the House of Representatives. I do not know how the previous speaker looks on that. If he thinks they are out of place, I disagree with him. I would not mind seeing the proportion largely increased.

As to the way our laws are made, let me quote from an address made last year by a lawyer, lawmaker, and statesman respected by all, irrespective of party—Elihu Root: " We make too many laws. Our national and state legislatures passed 62,014 statutes during the five years from 1909 to 1913 inclusive. During the same five years 65,379 decisions of the national and state courts of *last resort* were reported in 630 volumes. Of the statutes 2013 were passed by the national Congress; and of these decisions 1061 were rendered by the Supreme Court of the United States.

" Many of these statutes are drawn inartistically, carelessly, ignorantly. Their terms are so vague, uncertain, doubtful, that they breed litigation inevitably."

We talk about the great achievements in engineering, and I think, as a rule, even we engineers are apt to think of the influence of our profession as exerted through these great achievements, like the Panama Canal, the building of our great subways, the great hydroelectric installations, etc., but do we reflect that practically every thing in our daily life is involved with engineering? If we walk through the streets and look into the shop windows, no matter what kind of a shop it is, we have evidence of the engineer's work in one way or another. If that is so, why is it that in connection with the laws that are made to govern or misgovern these people, the engineer should not be in evidence more than he is? It is partly his own fault, I am afraid, partly because he has not felt that he was called upon to take up the duty of doing his best to influence public affairs.

I have had occasion many times to talk these matters over with engineers, and have had them say to me over and over again: "Well, that is not my business." It is their business, and it is our business, and distinctly so; we distinctly have the responsibility, for our training makes us peculiarly capable of solving some of these problems. The responsibility must accompany education and training; and before we complain too much as to present conditions we must recognize that we ourselves are in part responsible. It is not enough that we are ready to serve, but if necessary, we must force ourselves into the situation.

Now, how about these people who go to our legislative halls and say they reflect the will of the people? It is perfectly ridiculous. If a man goes to seek an advantage and by every sort of trick manages to make his point, does he reflect the attitude of those who surround him? Many of those who have been made his tools would not think of adopting his methods or his ideals. That sort of argument is funny, as the speaker said, but it is very far from convincing.

How about this joy of achievement? Again, should we not look at the little things as well as the big things? Should not we as engineers be more prepared than we are to get joy out of doing our work well all the time, in effort to keep up the standards, even where this involves repetition. Is there not a field in this country today with regard to this pleasure in doing work well? I know there is in the schoolroom, not only in the colleges, but in the graded schools. There is a distinct lack of the joy of achievement in the case of too many of our scholars.

There is at least one gentleman in the room who would be disappointed if I did not refer to the commissions. Why should the engineer be excluded from membership in the commissions? They are hired to serve the commissions, to do their bidding, but it is rather the exception when an engineer is appointed as a commissioner. Personally I believe that the present tendency towards commission control is absolutely in violation of our form of government. Again, I shall be misunderstood, I fear. I believe there should be commission regulation, not commission control. I believe that if engineers had been on these boards from the start there would be less tendency than has recently been exhibited to usurp the three functions of government, which, according to tradition and according to law in many of our States, is in violation of our form of government, namely, that the one body should exercise the three functions of government—the legislative, the executive and the judicial. These commissions all do exercise these three functions. I have had it stated to me by some of the commissions that the courts are above them, and so control the judicial function. Do not the lower courts exercise judicial functions, although they are subject to the court above them?

Judge Prouty in an address delivered about a year ago, after serving many years as the chairman of the Interstate Commerce Commission, and necessarily having had a large experience, while declaring his warmest admiration for his own profession, which he says is the greatest profession in the world —of course, there is always a difference of opinion in such matters—said he had come to the conclusion as the result of his experience that the engineer is *the* man for membership on these commissions, and then he states some things in which I agree with him, and some in which I do not. For instance, he states that engineering problems can be solved by mathematics alone. Nothing could be further from the truth, in my opinion. As Mr. Herr has stated, there are many other things besides mathematics to be considered, and one of the things which has to be used to a large extent in engineering is common sense, something that is not too much in evidence in our legislative halls today.

Judge Prouty then goes on to make an argument in favor of putting engineers on these boards. I do not mean that he favors putting engineers exclusively on these boards, nor do I. I think that the different vocations, the different activities, in life should be represented on these boards, and if a single engineer is sufficient then a single lawyer is sufficient. These boards should be made up of common-sense men, broadly trained, broad-minded, fair, and competent as investigators, and this irrespective of their professions. I do not by any means advocate putting engineers on these boards only because they are engineers, any more than we would advocate placing a lawyer on the bench simply because he is a lawyer. Judge Prouty himself in this statement says that the lawyer, naturally, is not of a judicial turn of mind. He is prone to be an advocate; whereas the engineer is prone to be judicial in his consideration of questions. I have often thought in connection with my experience with these commissions that if I could not do better with the law questions that are brought forward than the lawyer commissioners do with some of the engineering questions, I would retire from the witness chair.

Another member of the Interstate Commerce Commission—who, by the way, is not a lawyer, but a professor of economics—has come to the same opinion as that held by Judge Prouty, with regard to the desirability of having well-equipped engineers on these commissions. I confess I should expect to secure this admission from experienced members of the legal profession sooner than I would from theoretical economists.

As to this question of honesty. While we have always had the Ten Commandments to guide us we have of late years had them served up to us in many different forms, and generally as if they had not been brought to our attention before. Is it not true that the legislators and others in power today in this country are conducting themselves, and trying to conduct us, as if there were no real honesty in the country outside of the government circle? Is it not a fact that at every turn, business and enterprises of all sorts are being put on the defensive? It seems to be assumed that business men must be treated as if they were dishonest until they can prove to the contrary. Because there is dishonesty, and there always will be until the millennium—and in my humble opinion that will not be ever on this earth—because there is dishonesty, then must we regulate our affairs on the supposition that all are dishonest? We must put faith in the men who are doing the work of this world. I have had a pretty broad experience in many different lines. I commenced at it when I was very young, and I have been thrown in contact with men in many different lines of work, and I am glad to be able to say my experience has been that the great majority of men I have come in contact with are honest. There are dishonest men and we must guard against dishonesty as we find it in the minority, but that does not imply that every man with whom we do business for the first time must be put down as dishonest until he proves that he is honest.

Now, one of our greatest troubles today, in my opinion, is that because we have discovered dishonesty in some, we must regulate our affairs on the theory that all are dishonest. Personally, I object in my business affairs to the application of this theory.

Another thing: I believe that today we are submitting too timidly to this excess of regulation and control. While I do not believe it is for us to try to influence public opinion by devious methods, I do believe it is our duty to educate the public through frank statements of fact and arguments thereon reiterated as may be necessary; always being sure of our facts, and then having the courage to state them, even though we may fear that our personal interest for the time may be thus endangered.

Just one word in conclusion: I believe that engineers are better qualified than the men of any other one vocation or profession to help in bringing back this country to a sane regulation of its affairs.

ADDRESS OF GEORGE F. SWAIN

IT IS an opinion that is very widely held, and particularly among engineers, that the engineering profession is not appreciated at its full value, and that the engineer does not receive the recognition in public life and as a leader that his attainments entitle him to. In times past I have not hesitated on various occasions to raise my voice, feeble though it may be, in support of that proposition. I have not changed my views at all, and I agree with what has been said by previous speakers this evening in regard to that matter. However, it seems to me that by emphasizing continually what the engineer ought to have, we may possibly overdo somewhat that aspect of the matter. I am, therefore, going to ask you tonight to take a different point of view with me for a few minutes, and to consider, if the engineer has not received proper recognition, what the causes for this are, and how the existing condition may be remedied.

Of course, as a purely professional worker, the engineer is always necessary, and he will always be called upon to do engineering work. Moreover, statistics show that the remuneration which engineers receive is, on the average, as large as that received by members of the other professions. It is a question of supply and demand, and the engineering profession is not overcrowded. I feel certain of this from my experience in having turned out a great many young men year after year, and having placed them in positions.

Moreover, happiness and content, real success, service to mankind and to a man's family, do not depend upon money, and are not measured by dollars and cents, and can be obtained just as well when the remuneration is moderate as when the remuneration is very large; and engineers, as a rule, I believe, receive compensation sufficient to enable them to live comfortably.

Furthermore, in recent years the respect paid to the engineer, as well as his financial remuneration, have greatly increased. Engineers now frequently receive very large fees, fees that 25 or 30 years ago would have been considered almost out of the question. However, those fees are not as large as those sometimes received by lawyers or doctors, for the simple reason that the engineer does not appeal to sentiment, which is so potent a factor in the other professions. I presume that fear, love and avarice are the most powerful emotions of the human being. The law appeals to all of them; medicine appeals to fear and love; engineering appeals to none of them. Another potent factor in the human being is vanity. Architecture appeals to vanity. The architect can easily persuade his client to put up a costly and luxurious building, upon which he receives his percentage, the percentage increasing as the work is less and less necessary. The architect rightly puts a tax on luxury.

However, all of these matters in regard to the professional services of the engineer will take care of themselves. We are chiefly concerned here with the status of the engineer as a leader in the community, as a moving force, as an administrator or executor, who leads in the solution of great problems.

The suitability of a man for leadership depends upon two things—his knowledge and his personal qualities. Most of the great undertakings today, as has been said by speakers before me this evening, involve engineering; most of them, to a very great extent. Everybody recognizes this. We all know that we live in an age of applied science.

But law and business are equally necessary in the treatment of all of these great undertakings. There is no more reason, inherently, and no less reason, why the engineer should lead and be the employer, any more than why the lawyer or the business man should lead and be the employer. It gets down, therefore, in the end, to the matter of personal characteristics, as questions of this kind generally do. The man with the personality, if a lawyer or a business man, can easily lead, and can hire the engineering brains and knowledge, just as the engineer, if he has the personality, can lead and can hire the legal and the business brains and knowledge.

If, therefore, the engineer does not lead, it must be because he lacks the personal qualities of leadership; and if he lacks these personal qualities, he ought not to lead. There is no mystery about it, no injustice. By personal qualities I mean character, presence, tact, ability to handle men, breadth of mental vision, mental training.

Now, some of these qualities are inherent, and all may be developed more or less by training and experience. There is no reason to believe or to assume that one class of men in a community, in the same country and at the same epoch, is inherently superior, in regard to personal qualities, to any other class. Have we any reason to suppose that engineers are inherently superior to the members of other professions in this country? It does not seem to me that we have. What indications there are might be considered to point the other way.

This is a matter upon which a person cannot speak at all positively, or dogmatically, but I have talked with a good many college graduates as to what becomes of the men in their classes and I have been rather interested to find that they almost all tell me that the ablest men in their classes go into the law or into business. One thing, therefore, we must do is to try to do whatever is possible to induce the young men who are able, and of good character, to become interested in engineering, and to embrace it as a profession. We can all of us do something in that direction.

The problem is then reduced to this further question, whether the personal qualities that come by training, or are developed by training and experience, give to the members of the engineering profession preeminent qualifications for leadership. Those qualities which are most influenced by training and experience are mental grasp, ability to reason correctly, capacity to discern truth and a desire for attainment, and also the ability to deal with the human element. Now, it is generally claimed that the engineer should be particularly fitted, not only by his knowledge, which matter I have already referred to and disposed of, but because of his training, in ability to think straight, in breadth of view or grasp, in desire to get at the truth, and in the ability to discern the truth when he has arrived at it.

Now, how true are these claims? Do engineers think straighter than lawyers or business men? No positive statements can be made on a subject like this, and there are of course many exceptions to any statement that can be made, but I doubt whether engineers as a class think straighter than lawyers, especially, or the well-trained and experienced business man. The training of the lawyer in finding the exact meaning of terms is one of the most important factors in making him think straight. We all know how many misunderstandings and errors in reasoning come about because the exact meaning of the words or terms we use is not quite clearly understood. Ambiguity is one of the main sources of error in reasoning. The lawyer is continually concerned with getting at the exact meaning of words. In drafting statutes, in drawing wills, in all the varied work that he has to do, this is one of the practical courses of discipline which he goes through, and there certainly could be no better discipline.

Moreover, no man understands a question if he can only state it from the positive point of view; he must also be able to state it from the negative point of view; he must see not only what it *includes*, but what it *excludes*; he must see not only the arguments in favor of it, but the arguments against it. In that matter also, the lawyer has a most excellent training. When he assumes a case he puts himself in the position of his adversary and exerts his wits to the utmost to discover the weak points in his own case. He tries to discover every argument that can be brought up on the other side, and then prepares himself to meet them. I somewhat question if engineers in their experience go through quite as good a mental discipline as that, or whether in the school room they get anything that is quite as good a mental discipline.

I think, therefore, the legal training and experience, on the whole, probably trains men better to think straight or to reason logically, than engineering training. The single objection to the legal training is one that has frequently been mentioned, and has been previously referred to this evening, and that is that the lawyer is apt to become an advocate. But still we all know that there are many, very many, capable, high-minded lawyers who will not take a case unless they believe that they have the right on their side. Moreover, in human affairs, there is almost always something to be said on both sides of every question, and the lawyer who undertakes a case, should simply have for his object to see that the arguments on the side of his client are presented as strongly as possible, leaving it to the judge or the jury to decide on which side the right is to be found. It is not always a simple case of being in the right or in the wrong; it is more often a question of presenting fairly one side of a two-sided argument.

It is undoubtedly true, however, that there is a seamy side to the law, and that large numbers of members of that profession are dishonest, many of them mere blackmailers or ambulance chasers. To this class of men there is no parallel in the engineering profession, so that, taken as a whole, I believe, as I have frequently stated, that there is no more honest body of men than the members of that profession. There is abundant proof, however, that honesty of purpose and a desire to arrive at the truth may be misdirected, and that those qualities will not result in leadership unless combined with judgment, breadth of view, power of logical thinking and the ability to distinguish truth from error.

Now, how about breadth of view? Can we say that the engineer's training and experience give him a greater grasp, a greater mental breadth of view, than that of the lawyer or business man? Here again there may be doubt, but I similarly question whether today, and in the past, the training of the engineer has given him as much grasp and breadth of view as the training of the lawyer and the business man. I am afraid that the engineer concerns himself in college, and after college, too much with the minor technical details of his profession, does not accustom himself to study large questions, does not take interest enough in the consideration of the great problems affecting the community in general. I know that is so in the colleges. I know that the young men get interested in the purely routine technical details of the studies they are pursuing, and that it is difficult to get their minds away from these things to any large extent. Some men have such breadth of view, and get above the details of their profession, but many engineers seem to lack this quality and find it very difficult to acquire it.

The case with the business man is somewhat similar. I am a great believer in the business man, and I believe that his experience, bringing him in contact, as it does, with law, with engineering, with all the varied activities of public life, is a most excellent training. I should like to see more engineers in Congress, as has been suggested, I should like to see an engineer become the president of the United States, but I should like to see, for once, a really good, broad-minded business man in the presidential chair.

Instead of complaining, then, although it is true, that the engineer is not recognized, I urge that we try to realize, if this is so, that there is a cause for it. We live in a world of natural law. For everything that is, there is a cause, not only in the physical world, but in the mental and moral world; and this cause will always produce its effect. If the engineer is not recognized, therefore, let us see if we cannot find the cause and remedy it.

Among the things which I think we can do, are the following: We may exercise our influence to bring the facts in regard to the engineering profession, its possibilities, the high character of its work, to the attention of our young men in our schools, and to induce the honest and capable young men of the coming generation to embrace that profession. In the second place, we may influence technical education and try to secure a broader curriculum in our engineering schools, with more attention paid to fundamental principles and less attention to the technical details, which the graduate must learn in order to master his profession, and which he can learn a great deal better in the field after he graduates than he can in the school. Let us insist on a training of our engineering students in the English language, so that the engineers of the future shall not only be able to speak and express themselves clearly and lucidly, but may be able to write a proper report, and to impress upon people with whom they come in contact, not only that they are qualified in their engineering specialty, but that they are able to mix with men and to deal with large questions in a comprehensive way.

I agree entirely with what has been said in regard to mathematics. I think the fact that engineering is to so large an extent a mathematical subject is one of the main reasons why the engineer is not recognized. In my opinion, there is scarcely anything that tends more to narrowness of view than dealing all the time with problems that can be solved only by rigid mathematical processes, because the great questions which confront us, even in engineering, are not mathematical questions; the data are shifting and variable, and the human element comes in; therefore, the man who is accustomed to solve his problems by mathematics, and can only do the solving in that way, finds himself at a loss in the practical affairs of life, where mathematics do not apply. We should further seek to broaden the minds of our engineering students, as well as our own minds, by the study of history, literature, psychology and other subjects which give a broad outlook upon life.

I urge, therefore, that in these ways we help to make ourselves and the engineer of the future possessed of the personal qualities of leadership. We may rest assured that if we are possessed of these qualities, leadership will come to us.

ADDRESS OF HENRY G. STOTT

I FEEL that it is not necessary for me to apologize to you tonight when I say that I am going to be very brief. The hour is so late, and so many weighty matters have been presented to you tonight by the eminent gentlemen who have spoken to you, that I am quite sure what I have to say can be put before you in a very brief time.

I think that the present status of the engineer is quite satisfactory when we find on our platform tonight two engineers who are now presidents of two of our great corporations in this country.

There is one feature of the status of the engineer in this country, however, which is extremely unsatisfactory and absolutely unfair. I refer now to the many engineers who are employed by the United States Government. You hear of Major So-and-So, Colonel So-and-So, and Captain So-and-So, having charge of such and such a piece of work, a great piece of engineering work; but you never hear a word of the poor civil, mechanical or electrical engineer, who has actually done the work, and probably planned the whole thing. Our army engineers are very capable men, but they secured their high positions, as a rule, as executors, and did not do the actual engineering. That is one point on which we should all aim to help out our brethren who are employed by the United States Government, to secure a better recognition of their services. That is really a very important thing, I think, for engineers to remember, and they should keep it in mind wherever they can bring any influence to bear on the government officials.

About seven years ago, when you honored me by electing me president of this Institute, at the time when it came for the president to sing his "swan song," I made some remarks on the "Evolution of Engineering." In that address, which was given at Atlantic City, I quoted one of the oldest definitions of engineering that we have, that of Thomas Tredgold, who, about eighty-seven years ago, gave this definition: "Engineering: The art of directing the great sources of power in nature for the use and convenience of man." That is a very powerful definition and still holds to a great extent today. However, I showed in my address to which I have just referred, that, due to the evolution of engineering, we are constantly developing new specialties, that as the art developed and the particular branch which a man was working on became more important, it became necessary for someone, and perhaps many, to devote their entire attention and study to that one branch. We have at least fifty distinct and entirely separate branches of engineering today. While it is very necessary for a man to have a general knowledge of engineering, and of other subjects, in that connection I always think of a musical comedy which was presented in New York some years ago, in which one of the performers rendered a song or recitation, and in it he told about his father, who was a "musiker," but he could not play the violin because he had too many knuckles on his fingers, and could not play the trombone because he did not have wind enough, etc., and he finally settled down to play the bass viol. The moral which the performer drew from his father's struggle to play the different instruments was that "you can't play every instrument in the band." There is much truth and philosophy in that, and it stuck in my mind. We should specialize in some particular branch, and remember that we cannot play every instrument in the band. There are at least fifty different instruments in our band, and no man can play them all.

The developments of recent years, however, have brought us face to face with two types of engineers, those who specialize on one, or possibly two subjects, as one class; those men, I think, reap their reward in their achievements rather than in any great fame which may come to them. They certainly in their achievements have great reward. In another class are those who come to certain stages of endeavor by a process of natural selection, and naturally adapt their engineering principles to executive positions. We have on the platform tonight several notable examples of that kind. I take it that as long as men are not all made alike—no matter how evenly they may start with the same education, they all have different characteristics—each one must be developed along the line of his particular talent, so that while some may specialize, others will generalize.

And so, as in finishing up my address at the convention at Atlantic City, I will close with my own definition of engineering, which I made at that time, as being rather more applicable to the present development of the art:—"Engineering: The art of organizing and directing men and of utilizing the forces and materials of nature for the benefit of the human race."

ADDRESS OF J. J. CARTY

THE ENGINEER does not work in isolation. Like his fellows in the other learned professions his work is done in cooperation with those within and without his own profession. His work may be done through conscious cooperation, as in a corporate organization or learned society, or it may be done through that cooperation which he, like all others, exhibits as a member of organized society, and which is often most intense and effective when he is attending strictly to his own business, with no thoughts of cooperation in his mind.

From the dawn of engineering the work of the engineer has had to do with men as well as with things. The first rude implement shaped by the hand of man was designed to divide man's labor with him. In creating the first industrial and agricultural tools used by mankind the primitive engineer worked out a problem in organization, for the problem of organization is the problem of the division of labor. Labor may be done wholly by men and divided up among them in various ways according to their abilities, or it may be divided so as to be done partly by animals or partly by machinery provided by the engineer.

On account of the physical nature and oftentimes the monumental character of great works of engineering, the material side of the engineer's work has, until recent years, been its dominating characteristic, not only in the minds of the public but to a large extent in the minds of the engineers themselves. But a change has taken place. It has come about so rapidly and so imperceptibly that there has not been time even for the engineer himself to realize it, notwithstanding that to these changes he has been perhaps the greatest contributor.

The pure scientist, searching the unfathomable depths of nature to discover the wonderful truths there to be found, produces the raw material with which the engineer, with the powerful aid of his close ally, the chemist, constructs agencies which do so much to magnify the returns from the labor of man. From the dawn of history the work of the engineer has been to lighten the labors of man and to provide him with means of defense against his enemies. That these agencies provided by the engineer could be used for offense, as well as defense, and that they have been used in unjust, aggressive wars is the testimony of history. This evil is not to be ascribed to the work of the engineer. It is but a part of the crime of those who are responsible for waging an unjust war.

To understand the status of the engineer, we must appreciate his activities in war as well as in peace, and when peace comes again, and let us hope it will not be long delayed, astounding will be the story that will be told of how the agencies provided by the engineer have shared with man the labor of destruction.

Fortunate it is that we are not now compelled to consider the consequences of the engineer's efficiency in war, but that we can dwell upon the more salutary results of his efforts in the arts of peace.

During the last forty years, the increase in the means of transportation and communication, combined with the multiplication of improved labor-saving machinery in agriculture, mining and manufacture, which is so largely due to the engineer, has made possible in a higher degree than ever before that division of labor and that high state of differentiation in our industrial and commercial organization which are the mark of progress.

Everywhere that machinery is employed, the work of the engineer is plainly evident, even to the superficial observer. It can be allocated to a concrete, definite, physical thing. It is not so easy to see that in the design of this machinery the engineer had to consider his problem broadly as a problem in the division of labor, and that he had to determine at what point in the economic scale human labor could properly be superseded by that of the machine.

By such methods as these, the engineer long ago learned what is not yet sufficiently understood, that the problem of introducing a labor-saving machine is not solely a mechanical one. In addition to mechanics it involves economics as well as methods of operation. To the untrained mind the design of a machine to perform work formerly done by hand seems all that is required, but to the engineer, who is trained to consider these problems comprehensively, such a machine, however well it may operate, is not a labor-saving machine until the total annual charges lying against it are less than those which would be incurred if the work were done by hand. In this comparison, of course, the same quality of output is assumed. Unless equally good work can be done by the machine at lower annual charges, it is not a labor-saving machine, but rather a labor-increasing machine, substituting one kind of labor for another and more of it; but because this increased and substituted labor is performed in the mine, or at a distant factory, or elsewhere, it is not recognized by those minds which are capable of dealing only with simple, concrete things before their eyes which they can see and touch.

It is in the manifold nature of such problems as these that the ideals and imagination and those other mental processes of the engineer are brought to that high degree of development which lies at the foundation of all that is great in his achievements. The work of the engineer calls first for a correct ideal. While, as in other human affairs, it is not often that he attains an ideal solution of his problem, he understands the value of a correct ideal toward which, by the aid of an accurate and trained imagination, he directs his efforts.

In a distinguished way the work of the engineer, to be successful, must follow strictly in accordance with nature's laws. Before a human tribunal it might be proved by specious argument that an inadequate structure will sustain a maximum load or will withstand the severest action of the elements, but in the court of nature, before which all of the work of the engineer is ultimately tried, nothing will prevail but absolute compliance with its inexorable laws.

The historian of the future will say that perhaps more than any other class of men the members of the engineering societies which are represented here tonight and their fellow engineers elsewhere are responsible for the marvelous transformation which has taken place in the material conduct of human affairs during the lives of those now living.

This change has manifested itself in a striking manner in the growth of large organizations in all parts of the world. In communities and nations, as well as in corporate organizations, the same tendencies have been at work. Where formerly, units acted more or less independently and in isolation, they are now brought effectively into an organization which is nothing more than systematized division of labor between men and mechanism. All of this is made possible by the perfection of means of communication and of transportation of goods and people. Without these means cooperation between distant units would be impossible and coordination of men and machinery now effected over distances of thousands of miles would again be reduced to those primitive forms of control which can be used only when the units are close at hand, in office or factory.

This process of growth and differentiation which the engineer has done so much to promote has produced its effect upon the engineering profession itself. Engineers have increased in numbers and their work has been divided into branches. To the civil and mining and mechanical we have added the electrical and the chemical, and the electrochemical. Each branch has in turn thrown out from itself other branches until we have so many different kinds of engineers that I will not attempt to give the list, which includes farm, public relations, efficiency and commercial engineers.

With such a great growth in the number of engineers and in the importance and extent of engineering, it is inevitable and but a sign of progress that these differentiations should occur. Forty years ago there was no electrical engineer. Now electrical engineering is divided into specialties and even subspecialties. At the time of the Centennial Exhibition at Philadelphia there were no telephone engineers. Today in this country alone they are to be found by thousands.

It has been said that efficiency engineering is but a meddlesome interference with factory management; that commercial engineering very often contains no engineering whatever; that the farm and public relations engineer are but absurdities, and that some action regarding the abuse of the term "engineer" should be taken by the national engineering societies. But it seems to me that affairs are not so bad as all this; that there is much that is commendable in all of these movements; that they should be allowed to develop until they have assumed definite shape, and it can be seen whether they may not represent some most important activity to which perhaps only the wrong name has been applied. Such growths as these, if not fit to survive, can safely be left to that pruning process which nature sooner or later applies to all that is unfit.

There is no doubt that in the sudden growth of organization in mine and factory and on the farm and in commerce and transportation and communication, the engineer has often been admirably qualified to make that systematic division of labor among men, and between men and machines, which constitutes modern organization. When viewed as a problem in the division of labor as between man and machine how natural and easy has been the evolution of the efficiency engineer, who is really dealing with the problem of management, and who is calling his work by the name of " scientific management " instead of " efficiency engineering." It will be a great day for progress when "scientific" management can be merged with "common sense" management, each dropping the adjective and becoming plain *management*.

There is no doubt that some of the engineers with adjectives have been over-running the territory and encroaching upon the provinces of other branches of industrial and commercial activities, and that under the name of " engineering " they have been performing functions foreign to that profession. It is safe to say that this is because the sudden increase in the complexity of modern organization brought about by the use of scientific methods and mechanisms has obliged the manager to give more and more attention to scientific and engineering matters. Because of his lack of familiarity with these new changes he has been obliged to call to his aid the engineer and has been led to call by the name of " engineering " many activities which are really those of management and which, with the growth of the science of management, will in due course be called by their proper names.

In this there is a tribute to the engineer and at the same time a warning. It is coming to be recognized that the experience with men and things to be obtained in the practise of engineering is a valuable ingredient in that complex compound of which successful management is composed. The warning to the engineer is to check his activities as soon as he finds they are encroaching upon the province of other professions and other departments, to call things by their right names, and to recognize that within his own province there lies a career exceeded in usefulness by none of the other learned professions. By so doing he will best prepare himself to receive that recognition outside of his own profession which, at the dedication of this great engineering building, was prophesied for him by Dr. Hadley, the president of Yale, who said:

> " We have outgrown the day when a little common sense was sufficient for managing the affairs of the nation. They are become too complex and this complexity gives the engineer—if he will add to his training in mathematics a training in ethics and political economy and the fundamental principles of the law—an opportunity such as never before existed to claim and receive the position which rightfully belongs to him.
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> " We celebrate today and we are justified in celebrating the recognition of science as a necessary guide in the conduct of the material affairs of each man's business. Half a century hence, when our descendants shall meet in this building, or some yet greater building, I am confident that they will celebrate a yet greater thing, the recognition of the right of men of science to take the lead in enlightening the thought of the people on public affairs and the responsibility of filling the higher positions in the service of the commonwealth."

Although these words were spoken from this very platform less than ten years ago, yet in that short time so far has the status of the engineer been advanced toward the ideal set forth by President Hadley, that I am sure if he were here to-night he would not place that day which is to be celebrated so far away as half a century hence.

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DISTORTION OF ALTERNATING-CURRENT WAVE CAUSED BY CYCLIC VARIATION IN RESISTANCE

BY FREDERICK BEDELL AND E. C. MAYER

ABSTRACT OF PAPER

An alternating current flowing through an unvarying non-inductive resistance has a wave-form that is undistorted and is identical with the wave-form of electromotive force. If the resistance varies during each cycle, on account of changing current and temperature or other causes, the current wave-form will be distorted and will contain a third harmonic that will flatten the current wave when the temperature coefficient is positive and will peak the current wave when the temperature coefficient is negative.

If there is no temperature lag in the resistance (that is, if the maxima and minima of temperature and resistance coincide with the maxima and minima of current), the maximum of the third harmonic in the current wave will coincide with the maximum of the fundamental, so as to flatten or peak the wave as stated. A temperature lag in the resistance, however, causes the third harmonic of the current to be retarded in phase, and likewise causes a slight shifting of the fundamental of current with respect to the electromotive force.

Due to this distortion of current wave-form, power factor becomes less than unity and a vector diagram in more than two dimensions is required to show the true relations between current, electromotive force and power factor.

These conclusions, reached theoretically, conform with the experimental facts so far as known. In practical cases cyclic change of resistance is so small that the distortion due to it is insignificant.

IN A non-inductive circuit, the resistance of which remains constant during the cycle, an alternating current has exactly the same wave-form as the electromotive force impressed upon the circuit, for the current at each instant is directly proportional to the electromotive force at that instant. This is not true, however, if the resistance of the circuit changes during the cycle, as it does when the circuit consists of an incandescent lamp or lamps. In this case, since $i = e \div r$, the value of the current at any instant does not depend upon the electromotive force alone but depends also upon the value of the resistance at that instant; the wave-form of current is, accordingly, no longer the same as the wave-form of electromotive force. A simple sine electromotive force does not, in this case, produce a simple sine wave of current but a complex wave made up of a fundamental and one or more higher harmonics. It is the purpose of this paper to make a theoretical study of these harmonics and to see to what changes in resistance a particular harmonic corresponds. The conclusions which follow agree with experimental facts, so far as they are known.

If the resistance passes through the same series of values during the negative half-wave of current as during the positive half-wave, the negative half-wave will be a repetition of the positive, with sign changed, and, on account of this symmetry, the current wave can contain no even harmonics. (Even harmonics would be introduced, however, by a discriminating resistance having different values for positive and for negative currents; but it is not the purpose of this paper to consider resistances of this kind).

It will be shown later, in connection with Fig. 10, that no harmonic other than the third can produce an effect consistent with physical facts, if it alone is present or predominant. Particular attention will, therefore, be given to the third harmonic and the cyclic change in resistance corresponding to it.[1]

Let it be assumed that the electromotive force is a sine wave, as curve e in Figs. 1 to 6, and that the current, i, consists of a fundamental, i_1, and a third harmonic, i_3, with maximum value equal to ten per cent of the maximum value of the fundamental. The phase of the fundamental and of the third harmonic with respect to the electromotive force will be represented by θ_1 and θ_3, respectively.

Irrespective of the value of r, the current must be zero when the electromotive force is zero, for $i = e \div r$, and this fact has been made use of in constructing the curves.

In constructing Figs. 1 to 6, the procedure has been as follows: First the electromotive curve e, a sine curve, is drawn. The third harmonic, i_3, is then drawn in some assumed phase position, as shown by the figure and indicated by the value of θ_3. Next, the fundamental of current, i_1, is so located that, when the electromotive force is zero, i_1 and i_3 will have equal and opposite values; the total current i is thus made zero when the electromotive force is zero, a necessary condition, as already pointed out. Finally, the curve i for total current is drawn as the sum of i_1

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[1] A similar study has been made of the distortion of wave-form in a circuit embracing iron; see *Effect of Iron in Distorting Alternating-Current Wave Form*, by F. Bedell and E. B. Tuttle, TRANS. A.I.E.E., p. 671, Vol. XXV, 1906.

and i_3; and the curve r is drawn showing the instantaneous values of resistance, $r = e \div i$.

On the right, in each figure, the broken curve r shows the value of resistance for each value of current; the solid curve shows the relation between e and i. Except in Figs. 1 and 4, it will be seen that r and e have different values for increasing and decreasing values of i.

Discussion of Curves. Fig. 1 shows that a third harmonic of current in phase with e, ($\theta_3 = 0$), flattens the current curve and corresponds to a resistance that increases with current, that is, the temperature coefficient is positive. Maximum resistance occurs, in Fig. 1, at the same time as maximum current; hence, in this case, there is no temperature lag. It is seen that the resistance has the same value for increasing and for decreasing current.

Since the resistance curve has maxima for negative and for positive current, the resistance curve has twice the frequency of the current curve.

Fig. 2 shows the same case as Fig. 1 except that the third harmonic of current is caused to lag a little, with respect to the electromotive force. As a result, the fundamental, i_1, is seen to be advanced in phase so that the sum of the fundamental and third harmonic of current is zero when the electromotive force is zero. The maximum resistance is now reached later (approximately 30 deg. later) than the maximum current, indicating a temperature lag. Resistance increases with current, indicating a positive temperature coefficient, but the maximum resistance is now reached later than the maximum current, and the resistance has different values for increasing and decreasing current, due to this temperature lag.

The curves on the right, accordingly, show resistance hysteresis loops.

Fig. 3 is the same as Fig. 2 with θ_3 increased to 30 deg. θ_1 now has its greatest possible value, for further increase of θ_3 decreases θ_1, as shown in Fig. 7.

Curves, not shown, have been drawn similar to Figs. 2 and 3 for all ranges of value of θ_3; the figures reproduced here are typical. They agree remarkably well with the experimental curves of Sahulka[2] and Bedell[3] made with incandescent lamps. These

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[2] "Wave Forms of Current and *Cp* of Alternating-Current Lamps," by J. Sahulka, *Elec. World Digest*, p. 803, Vol. 49, 1907; original article in *Elek. und Masch.*, Feb. 17 and Mar. 17, 1907.

[3] "Measurement of Instantaneous Lamp Resistance," by F. Bedell, *Elec. World*, p. 370, Vol. 57, 1911.

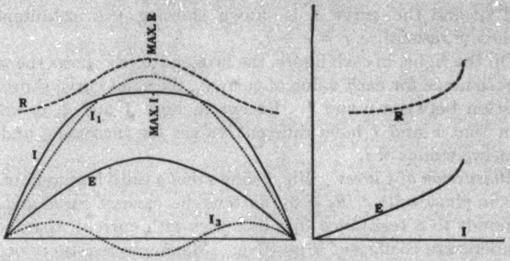

FIG. 1. $\theta_3 = 0$. θ_1 IS THEN 0; I_1 AND I_3 ARE IN PHASE WITH E. MAXIMUM R COINCIDES WITH MAXIMUM I AND THERE IS NO TEMPERATURE LAG. TEMPERATURE COEFFICIENT IS POSITIVE

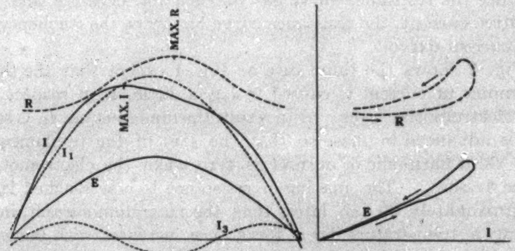

FIG. 2. $\theta_3 = -6°$ (APPROX.), I_3 BEING RETARDED IN PHASE. I_1 IS THEN ADVANCED SO THAT $\theta_1 = +2°$. MAXIMUM R LAGS 30° BEHIND MAXIMUM I, DUE TO TEMPERATURE LAG. TEMPERATURE COEFFICIENT IS POSITIVE

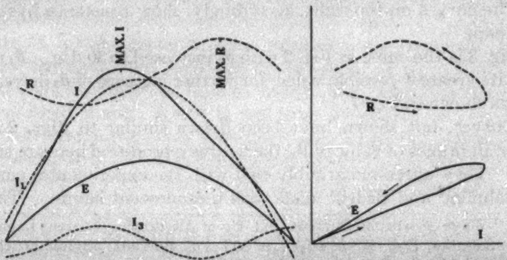

FIG. 3. $\theta_3 = -30°$, I_3 BEING FURTHER RETARDED; I_1 IS THEN ADVANCED SO THAT $\theta_1 = +5.75°$. MAXIMUM R LAGS 60° BEHIND MAXIMUM I DUE TO TEMPERATURE LAG. TEMPERATURE COEFFICIENT IS POSITIVE

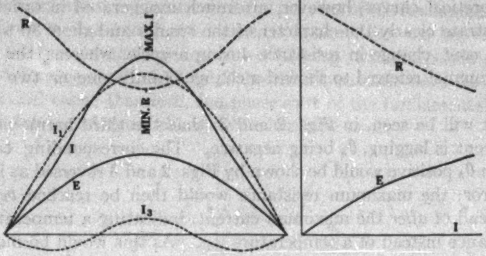

Fig. 4. $\theta_3 = -60°$. θ_1 is then 0. I_3 is just Opposite to I_3 in Fig. 1. Minimum R Coincides with Maximum I and there is no Temperature Lag. Temperature Coefficient is Negative

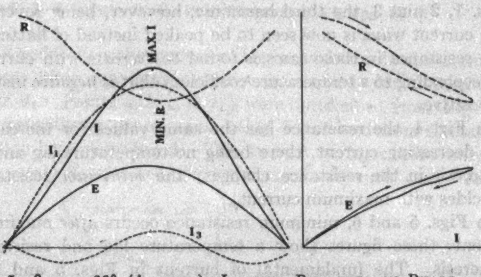

Fig. 5. $\theta_3 = -66°$ (Approx.), I_3 being Retarded in Phase. I_1 is then Retarded so that $\theta_1 = -2°$. Minimum R Lags 5° behind Maximum I, due to Temperature Lag. Temperature Coefficient is Negative

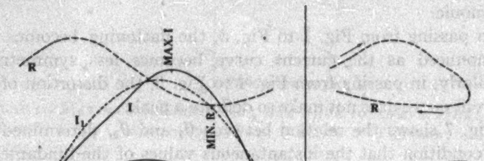

Fig. 6 $\theta_3 = -90°$, I_3 being Further Retarded. I is then Retarded so that $\theta_1 = -5.75°$. Minimum R Lags 30° behind Maximum I. Temperature Coefficient is Negative theoretical curves, however, are much exaggerated in order to illustrate clearly the character of the results and show 30 to 40 per cent change in resistance during a cycle, whereas the experiments[4] referred to showed a change of only one or two per cent.

It will be seen, in Figs. 2 and 3, that the third harmonic of current is lagging, θ_3 being negative. The corresponding cases with θ_3 positive would be shown by Figs. 2 and 3 reversed as in a mirror; the maximum resistance would then be reached *before* instead of *after* the maximum current, indicating a temperature advance instead of a temperature lag. As this would be inconsistent with physical fact, it may be concluded that the third harmonic must lag as shown in Figs. 2 and 3.

Figs. 4, 5 and 6 show cases corresponding to those shown in Figs. 1, 2 and 3, the third harmonic, however, being reversed. The current wave is now seen to be peaked instead of flattened. The resistance in these cases is found to *decrease* with current, corresponding to a temperature coefficient that is *negative* instead of positive.

In Fig. 4, the resistance has the same values for increasing and decreasing current, there being no temperature lag and no hysteresis in the resistance changes; the *minimum* resistance coincides with maximum current.

In Figs. 5 and 6, minimum resistance occurs *after* maximum current; these figures show a temperature lag and resistance hysteresis. The fundamental of current in Figs. 5 and 6 is lagging instead of in advance of the electromotive force, as in Figs. 2 and 3, so that its value at the moment of zero electromotive force will be equal and opposite to the value of the third harmonic.

In passing from Fig. 1 to Fig. 3, the flattening becomes less pronounced as the current curve becomes less symmetrical. Similarly, in passing from Fig. 4 to Fig. 6, the distortion of the current curve does not make so definite a peak.

Fig. 7 shows the relation between θ_1 and θ_3, determined by the condition that the instantaneous values of the fundamental and third harmonic must be equal and opposite at the moment when the electromotive force is zero. Fig. 7 is drawn for the case in which the third harmonic is ten per cent of the fundamental. Even in this exaggerated case, it is seen that the lag or lead of the fundamental cannot exceed 5.75 deg., and this possible phase difference would be less if the third harmonic were less. In practical cases, therefore, the phase shift of the fundamental current due to resistance change will always be small.

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[4] Experiments might be made with resistances having a much higher temperature coefficient than incandescent lamps. A boron resistance has been described by Dr. E. Weintraub, the conductivity of which doubles for 17 deg. cent. change in temperature; see *Elec. World*, Vol. 63, p. 1098, May 16, 1914.

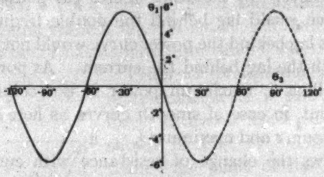

FIG. 7—VALUES OF θ_1 FOR DIFFERENT VALUES OF θ_3

Figs. 8 and 9 show the amount of lag in maximum or minimum resistance, after maximum current is reached, for different values of θ_3. Points *a*, *b*, *c*, *d*, *e*, *f* were determined from Figs. 1 to 6, respectively, other points being determined from similar curves not here reproduced. The amount of lag can be only approximately determined from the curves in each case. In

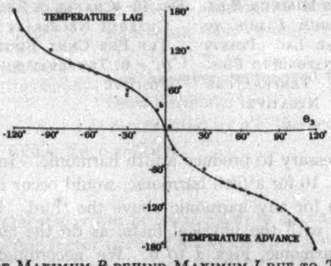

FIG. 8—LAG OF MAXIMUM *R* BEHIND MAXIMUM *I* DUE TO TEMPERATURE LAG. POINTS *a*, *b*, *c* CORRESPOND TO FIGS. 1, 2 AND 3, TEMPERATURE COEFFICIENT POSITIVE

view of this fact the results in Figs. 8 and 9 seem quite consistent. In Figs. 7, 8 and 9, negative values of θ_3 correspond to temperature lag; positive values would correspond to a temperature advance, as already pointed out.

In the foregoing discussion, resistance has been considered as a function of current, the relation between resistance variation and wave form of current being the object of the investigation. If, in Figs. 1 to 6, curves were drawn for instantaneous power, by taking the product $e \times i$, these curves, as is well known, would be curves of twice the frequency of e or i. In Figs. 1 and 4 the double frequency curve for r would have its maxima and minima (or minima and maxima) coincident with the maxima and minima of the power curve. In the other figures the double frequency resistance curve would lag behind the double frequency power curve, and this lag behind the power curve would not be identical in amount with the lag behind the current. As power depends upon e as well as i, maximum power is not coincident with maximum i, but, in case of smooth curves as here discussed, is between maximum e and maximum i.

Fig. 10 shows the change of resistance with current which would be necessary to produce a fifth harmonic. Inflections, as shown in Fig. 10 for a fifth harmonic, would occur in resistance curves drawn for any harmonic above the third. Such curves do not agree with the physical facts, as do the curves drawn for a third harmonic, Figs. 1 to 6. We accordingly conclude that the third harmonic must be predominant and that any higher harmonics must be relatively small.

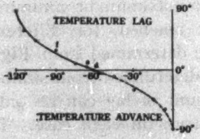

FIG. 9—LAG OF MINIMUM R BEHIND MAXIMUM I DUE TO TEMPERATURE LAG. POINTS d, e, f CORRESPOND TO FIGS. 4, 5 AND 6; TEMPERATURE COEFFICIENT NEGATIVE.

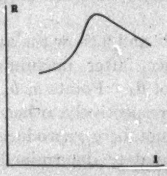

FIG. 10—CHANGE OF RESISTANCE WITH CURRENT NECESSARY TO PRODUCE A TEN PER CENT FIFTH HARMONIC; $\theta_5 = 0$; TEMPERATURE COEFFICIENT POSITIVE

Power Factor. With a sine electromotive force, there is power in the fundamental current only, there being no power in any harmonic in the current that does not have a corresponding harmonic in the electromotive force. The true power is, accordingly, $E\, I_1 \cos \theta_1$. The apparent power is EI, where I is the effective value of the total current; $I^2 = I_1^2 + I_3^2 + I_5^2 + I_7^2 \ldots\ldots$

Power factor, the ratio of true to apparent power, is, accordingly, equal to cos $\theta_1 \times I_1 \div I$, being the product of the fundamental power factor and a distortion factor, $I_1 \div I$, always less than unity. Power factor is independent of θ_3.

A third harmonic of ten per cent gives a distortion factor of 0.995 and, for the cases shown in Figs. 1 to 6, the power factor is cos $\theta_1 \times 0.995$. When $\theta_1 = 0$, Figs. 1 and 4, the power factor has its maximum value 0.995. When $\theta_1 = 5.75$ deg., Figs. 3 and 6, the power factor has its minimum value 0.990.

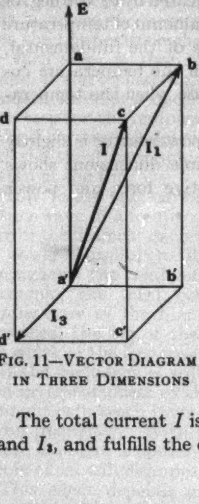

FIG. 11—VECTOR DIAGRAM IN THREE DIMENSIONS

Vector Representation. The vector representation of a sine electromotive force, E, and a distorted current, I, is shown in Fig. 11. The fundamental plane (the plane of the paper) is determined by E and the fundamental current, $I_1 = a'b$, the phase difference between them being $\theta_1 = aa'b$.

The third harmonic current, I_3, is represented by $a'd'$ at right angles to the fundamental plane,[5] irrespective of the value of θ_3. (This line represents any harmonic, not necessarily the third. If several harmonics are present, it represents their combined value, $I_h = (I_3^2 + I_5^2 + I_7^2 + \ldots\ldots)^{\frac{1}{2}}$. It will, however, be referred to here as the third harmonic.)

The total current I is represented by $a'c$, the vector sum of I_1 and I_3, and fulfills the condition

$$I^2 = I_1^2 + I_3^2.$$

The fundamental power factor is cos $\theta_1 = \cos aa'b$.

The distortion factor (as used above) is $I_1 \div I = \cos ca'b$.

The total power factor, or cos θ, is the product of these two, that is,

$$\cos\theta = \cos\theta_1 \times I_1 \div I;$$

or, $\cos aa'c = \cos aa'b \times \cos ca'b$.

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[5] This representation of harmonics by vectors out of the fundamental plane was described by one of the writers at a meeting of the Physical Society in June, 1906; see "Note on the Graphical Representation of Non-Sinusoidal Alternating Currents," by F. Bedell, *Phys. Rev.*, Vol. XXIII, p. 249; also Bedell and Tuttle, *loc. cit.*

It is seen that, unless I_3 is zero and the current is a sine wave, there is no value of θ_1 that brings I in phase with E; that is, θ is never zero and cos θ is never unity.

Summary. Cyclic change in resistance distorts the current wave and this distortion is accounted for chiefly by the introduction of a third harmonic. This harmonic has such a phase position as to flatten the current wave slightly when the temperature coefficient is positive and to peak the wave when the temperature coefficient is negative. The third harmonic lags in phase, from a symmetrical position indicated by $\theta_3 = 0$ deg. or 60 deg., by an amount dependent upon the amount of temperature lag; this causes a slight shifting in phase of the fundamental, advancing the fundamental in phase when the temperature coefficient is positive and retarding it in phase when the temperature coefficient is negative.

On account of the distortion of current, power factor is slightly less than unity. A vector diagram in three dimensions shows the relations between current, electromotive force and power factor.

DISCUSSION ON "DISTORTION OF ALTERNATING-CURRENT WAVE FORM CAUSED BY CYCLIC VARIATION IN RESISTANCE" (BEDELL AND MAYER) NEW YORK, FEBRUARY 18, 1915.

Clayton H. Sharp: I could wish that Dr. Bedell would carry his analysis a step further, and apply it to the condition of alternating-current operation of lamps. When that is done, a number of other factors evidently enter which introduce considerable complication. As I understand the analysis which is given here, Fig. 1 represents what might be called the statical condition, that is, where the frequency of the alternating current is so low that the temperature changes have time to equalize themselves for each step, so that there is no temperature lag. In other words, it corresponds to what we should have if we carried the filament through a cycle of steps and gave it sufficient time at each step for the temperatures to become steady. In that case, a third harmonic is introduced into the fundamental sine wave, and the third harmonic is so phased as to cause the wave to flatten at the top.

Now, in the next curve, the condition corresponds to an alternating wave of a frequency sufficiently high so that the temperature of the filament cannot reach its ultimate value for each value of power supplied to it. Hence there is a temperature lag throughout, the result of which is seen to be a lag of the third harmonic, the third harmonic remaining in phase with the temperature of the filament. If the frequency is still further increased, the lag of the third harmonic is also increased, and the width of the hysteresis loop is made greater.

If the frequency is still further increased, the effect of distortion or lopsidedness of the wave, due to the thermal lag in the filament, will reach its maximum value for a given filament at a given frequency. With very high frequency the cyclic changes in the filament temperature will be zero, practically, so that the whole effect will disappear.

This effect depends upon the diameter of the filament, its thermal conductivity, the emissivity of its surfaces, and its specific heat; hence its analysis must be quite complicated.

A few years ago I presented an attempt to detect by oscillograms any shifting of the current wave with respect to the voltage wave in a tungsten lamp. In order to make the effect greater —for what I was really looking after was power factor, which Dr. Bedell has shown to be small—I introduced not only the third harmonic, but also the fifth one, so as to get a very peaked wave, with the idea that the changes in temperature would lag further behind the changes in electromotive force, if the electromotive force had very sudden changes due to its peaked character. By the use of a bridge method a certain difference was found between the resistance with alternating current and direct current, but the power factor came out so very near 100 per cent that I have never been sure of the exact value.

C. Field-Frank: Professor Bedell has called attention only to those substances which obey what we may call Ohm's law, that is to say, those substances where the instantaneous application of electromotive force results in a straight-line relation between itself and the current which flows. A very interesting field is opened up, however, once we consider the conductivity of those substances which do not obey this straight-line law. We have this condition in any path containing a number of loose contacts, such as the common coherer.

The study of conduction in a path containing an accumulation of particles is a very large field, in which a great deal of work has been done. I will take just a minute, however, briefly to indicate how nicely Professor Bedell's "hysteresis loop" is brought forth in substances of this nature. Let us consider a coherer consisting of a glass or other insulating tube *A*, (see Fig. 1);

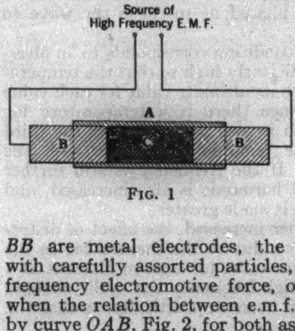

FIG. 1

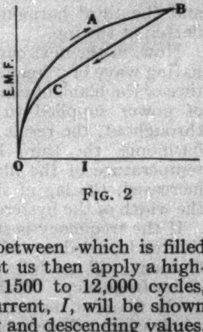

FIG. 2

BB are metal electrodes, the space between which is filled with carefully assorted particles, *C*. Let us then apply a high-frequency electromotive force, of from 1500 to 12,000 cycles, when the relation between e.m.f. and current, *I*, will be shown by curve *OAB*, Fig. 2, for both ascending and descending values. The equation of this curve is $E = k\,I^n$, where n has been about 0.3 for a large number of substances I have studied. If we gradually reduce the frequency, the descending curve *BCO* will vary from the ascending more and more, as shown in the figure, giving a perfect imitation of a "hysteresis loop."

Where the return curve *BCO* is below the ascending, the thermal coefficient of electrical conductivity is, of course, negative. And this brings us to a case where we can get in practise something which corresponds closely to Prof. Bedell's Fig. 10. This is accomplished by mixing our particles, *C*, or by introducing two coherers in series, one containing particles having a negative temperature coefficient, such as carborundum; the other having a positive temperature coefficient, such as iron or nickel, or even, under some conditions, merely by introducing an ordinary iron resistor in the circuit of the coherer having the negative temperature coefficient.

The utility of such unusual combinations is surprising, and I do not doubt but that the near future will see several taken out of the laboratory for service.

L. W. Chubb: The study of distortion of current as a function of resistance has been very interesting, but in most cases such distortions are more of scientific interest than of commercial value. Now and then, however, these cyclic variations cause disturbances which are of importance and the governing laws and constants of the circuits and materials need careful consideration. Lightning arresters, both the electrolytic and resistance types, rectifiers with batteries, furnace resistors and circuits containing arcs are some of the things which cause such disturbances and in which the apparent resistance is a function of current, voltage or temperature.

The authors call particular attention to the distortions of current in the incandescent lamp due to cyclic variations of resistance as a function of temperature, and to the predominating effect of the third harmonic.

Practically all of the energy of the lamp is dissipated by radiation. Conduction and convection are negligible but thermal capacity has an appreciable effect in causing a temperature lag, even at the lowest commercial frequencies. If we assume the radiation to be proportional to the difference of the fourth powers of the temperatures, the temperature coefficient of resistance to be a constant, and a reasonable figure for the thermal capacity, it can be shown mathematically from the differential equation of the lamp that when operated on a sine voltage, the third harmonic component will predominate in the distorting current. Whether this component alone causes the distortion is difficult to show mathematically. Experimental results, however, show the presence of other harmonics, but in small amounts.

With regard to the loops which the authors show at the right of each curve, I wish to add that since the voltage is a simple harmonic function the loop is easily resolved into Lissajous figures combining this voltage and the several harmonic currents at right angles. The areas of these loops represent the reactive energy, and similar loops constructed by combining the distorted current and sine voltage with the voltage shifted 90 deg. will represent the true power expended. The use of such loops is a very efficient method of figuring true power, reactive power, and power factor where only the two waves of voltage and current are given and one of them is a sine wave.

It is not necessarily true that the fundamental component must lead or lag when the distorting third lags or leads, unless there are no other harmonic components of current. The negative ordinate of the lagging third harmonic when the voltage is zero may be offset by a resultant positive ordinate or sum of ordinates of harmonics above the third. Recent experimental results with 10-watt, 110-volt lamps on a 25-cycle sine wave voltage show that the fundamental leads slightly but not enough to offset as much as half of the third harmonic ordinate when voltage is zero. Upper harmonics occurring in decreasing amounts make the current wave zero when the voltage is zero.

Charles R. Underhill: When an e.m.f. is impressed upon a solid metallic conductor which is non-inductively arranged, all of the electrical energy is converted into heat: another form of energy.

The heat energy converted is proportional to mass times difference in temperature, which seems to indicate that temperature is proportional to the square of a velocity. According to the theory of heat, the particles of solid matter oscillate in increasing orbits as the temperature increases, thus causing expansion of the body heated. In general, as the body expands, the resistivity increases; that is, the temperature of the body is a measure of its resistivity and vice versa. Volume resistivity is usually defined as the resistance (in microhms) between opposite faces of a centimeter cube of the material. *It may also be defined as the uniform cross-sectional area in sq. cm. of a piece of the material which, at one volt per cm. length, will develop heat at the rate of one watt per cm. length.*

In the electromagnetic system of units, resistance is a velocity; in the electrostatic system it is the reciprocal of a velocity, while, in metals, at the absolute zero of temperature resistance is assumed to disappear entirely. In the case of an electric lamp, the energy is radiated away about as fast as converted and, in alternating-current systems, there are cyclic changes, in the resistance of the filaments as set forth in the paper, but, if it is assumed that all of the electrical energy applied to the mass of the conductor remains there in the form of heat, and is not radiated or conducted away, it is remarkable how much energy can be stored in, say, a mass of ten grams of copper without materially increasing its volume, when reckoned from the absolute zero of temperature.

Again referring to volume resistivity ρ, there are three general definitions which refer to the spatial relations of the material; some fixed temperature being assumed. They are,

1. *The resistance per cm. length of a conductor ρ sq. cm. in cross-section is one ohm.*

2. *In a perfectly square sheet of conducting material ρ cm. thick, but with any length of edge, the resistance between any two opposite edges will always be one ohm.*

3. *In a cube of conducting material ρ cm. per side, the resistance between any two opposite faces is one ohm.*

In the above, the sheet described in (2) may be thought of as being rolled up to form a solid circular conductor which shall always have a resistance of one ohm. Its cross-section will be equal to $\rho \times$ length, and will vary with variations in temperature when the length is kept constant.

M. G. Lloyd (by letter): The authors have shown the relation between pulsating resistance and current, assuming sinusoidal e.m.f. This condition occurs especially in incandescent lamps, the magnitude of the effect increasing as the frequency is lowered and the filament made thinner. It is of interest to consider also the relation of power to resistance under such circumstances.

In a paper presented at the Minneapolis meeting of the American Association for the Advancement of Science* I showed that where there is no lag of temperature (and hence resistance) behind current (as in Figs. 1 and 4) the power is greater for a negative temperature coefficient of resistance (Fig. 4) and less for a positive coefficient (Fig. 1) than for continuous current. This assumes the same effective value of voltage in both cases. The effect is a maximum for no lag of the temperature, and decreases as the lag increases, until for a lag of a quarter cycle it becomes zero.

The candle power of an incandescent lamp is, however, always greater for alternating than for continuous current, whether the filament be of carbon or tungsten. The effect is negligibly small under most conditions, but becomes appreciable in a 25-watt, 116-volt tungsten lamp operated at 25 cycles, where it was found to be 1.6 per cent. With thicker filaments and higher frequencies the effect is of course less.

Frederick Bedell: This work was approached from the standpoint of alternating-current theory. In years past I have had the pleasure of presenting before this Institute, and elsewhere, certain conclusions that are applicable to alternating-current circuits in which the resistance, self-induction and capacity are constant. This limitation has stared us in the face for years and for some time I have been endeavoring to see what could be done with reference to removing it.

In a previous paper, by Bedell and Tuttle, the question of hysteresis of iron and variable inductance has been considered, and the fact was brought out that the variation there considered brings in predominantly a third harmonic. This investigation with reference to a varying resistance leads to a similar result, and, as Mr. Taylor has emphasized, it is seen that there is a physical reason for the existance of the third harmonic. The numerical effect, however, is not very large, scarcely affecting the practical results of our equations and diagrams as hitherto used; that conclusion alone, I think, is worth while. It was to point out particularly just what modifications should be introduced in our previous treatment, in order to make it exact, that this investigation was undertaken.

It is true, as Mr. Chubb remarked, that the shifting in phase

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***Electrical Review and Western Electrician*, Vol. 58, p. 94, **Jan. 14,** 1911.

of the fundamental of current would be modified by any harmonic higher than the fifth. Several of the speakers have indicated the possibility of making the investigations more extended and general—Dr. Sharp and Mr. Chubb by considering the emissivity and radiation constants; and Mr. Field-Frank by considering that the resistance does not necessarily follow Ohm's law, as considered in this paper.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 18, 1915, under the auspices of the Electric Lighting Committee.

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DIMMERS FOR TUNGSTEN LAMPS

BY ALFRED E. WALLER

ABSTRACT OF PAPER

The advent of tungsten lamps for theater lighting made necessary a complete re-design of the dimming apparatus.

Dimmers designed for the control of carbon filament lamps do not give smooth and flickerless regulation when used with equal loads of tungsten lamps. This is due to the temperature coefficient of resistance of the lamp filaments, that of the carbon filaments being negative, and that of the tungsten filaments positive.

Curves are shown to indicate the change in lamp resistance and candle power for various watt inputs. Curves for both carbon and tungsten filament lamps are shown in order to bring out the contrast, and a method is described for determining the resistance per step and number of steps in the dimmer designed for control of tungsten lights.

Following is a brief indication of commercial requirements in dimmer design.

ONE OF the changes brought about by the introduction of tungsten lamps has been a complete redesign of the apparatus used for lamp dimming in theatrical work.

At the time when tungsten lamps first came into general use the design of theater dimmers for carbon lamps had become fairly well standardized. A rheostat with 50 steps of resistance, and a taper of approximately 5 to 1 in ampere capacity, had been found entirely adequate and satisfactory, and this design was practically universal.

The controllers, or dimmers, to use the trade name, which were built to regulate the illumination of carbon lamps were found unsatisfactory, however, when the carbon lamps were replaced by lamps having metallic filaments such as tungsten. Metallic filaments have a positive temperature coefficient of resistance, while carbon filaments have a negative temperature coefficient of resistance. For instance, if we start with two filaments of the same resistance, one of carbon and one of tungsten, and raise them to incandescence, the tungsten filament at its full incandescence will have thirty-five times the resistance of the carbon filament at its full incandescence. On account of this disparity, the control of tungsten lamps by dimmers designed for carbon lamps was uneven, the lights flickered considerably, and in some cases it was found that desirable lighting effects obtained in the past could not be duplicated.

A comparison of the resistance characteristics of the carbon and tungsten filaments in actual operating conditions served to indicate the reason for this difficulty, and it is by reviewing this comparison that the problem may be most readily understood.

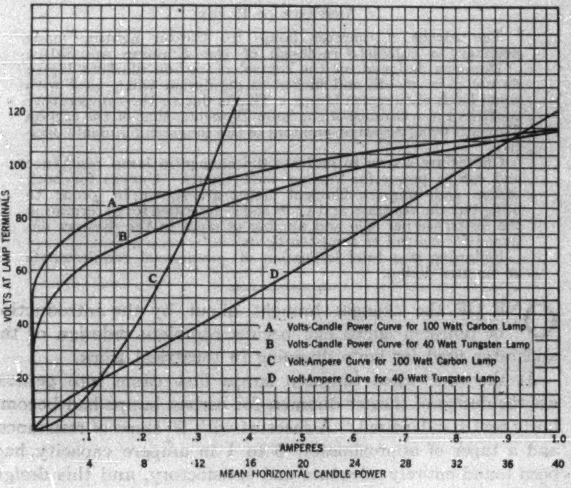


FIG. 1

The curves shown in Figs. 1 and 2 were plotted from a table of readings obtained by varying the potential at the terminals of a test lamp, in two-volt steps from zero to 126 volts, and recording the amperes flowing and candle power emitted at each step. The lamps used were a 40-watt tungsten, and a 100-watt carbon filament lamp, both rated at 110 volts. These were selected because their candle power at full voltage is practically the same, and an opportunity is thus afforded to compare the dimmers required for controlling installations of either type having approximately the same total candle power.

The design of a dimmer for carbon lamps is a comparatively simple matter. It will be noted that curve *A*, Fig. 2, which is that of a carbon lamp, has very little inclination between the 10-watt and 100-watt abscissas. This indicates that there is little change in resistance of the carbon filament between these points, which represent approximately the practical working range of the lamp. In order that the lamps when in use may be totally extinguished without opening the circuit, it is customary to build the dimmer with enough resistance to reduce the input somewhat below 10 watts, or, in the case of this particular lamp, to approximately 6 watts. At this input, which

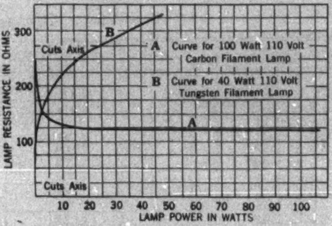


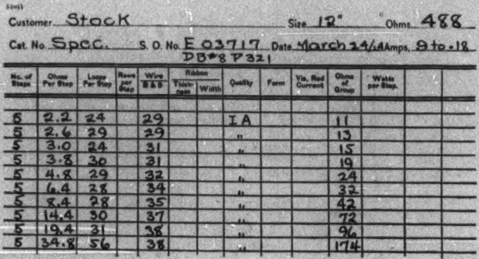
FIG. 2

is attained at 28 volts, the filament is at "visible red"—that is, it may be distinguished as a faint red line, if kept in a perfectly dark room. Not until the applied voltage is 48 volts do we obtain one-tenth of one candle power.

The calculation of the resistance per step of a dimmer for this type of lamp would be similar to the computation of a generator field rheostat, or any other controller designed for operation in series with a substantially constant resistance across a constant supply voltage. The full rated current of the lamp is 0.9 ampere, the minimum to which we will reduce this by means of the rheostat, 0.18, the line potential 110 volts, and the working resistance of the lamp 122 ohms approximately.

At the minimum current of 0.18 ampere the lamp resistance is actually 138 ohms, but the increase in resistance takes place after the lamp has, so to speak, ceased to exist as an illuminant, and for this reason, in designing, it is convenient and entirely satisfactory to assume the resistance as constant at 122 ohms. The only effect which this assumption has on the design is to increase the resistance of the rheostat slightly beyond what is absolutely necessary, thus permitting the "dimming out" mentioned in a previous paragraph. It may be noted at this point that dimming to visible red is not usually necessary. The general requirement is met by a dimmer which will reduce the illumination to a point where it is no longer perceptible on the stage.

A typical data card of a carbon filament dimmer is reproduced in Fig. 3. The steps of resistance are divided into groups, as will be noted, for convenience in manufacture. This does not in any way alter the correct operation of the dimmers; if the steps are calculated one at a time it will be found that those adjacent vary by amounts too small to be taken into account in this kind of work. The change in resistance per step when we proceed from one group of steps to the next becomes insignificant if we compare the resistance of the step with the total amount of resistance then in circuit.



Customer Stock Size 12" Ohms 488
Cat. No. Spec. S. O. No. E 03717 Date March 24/14 Amps. 9 to .18
DB#8 P321

No. of Steps	Ohms Per Step	Loops Per Step	Rows per Step	Wire B&S	Ribbon		Quality	Form	Vis. Red Current	Ohms of Group	Watts per Step		
					Thickness	Width							
5	2.2	24		29			IA			11			
5	2.6	29		29			″			13			
5	3.0	24		31			″			15			
5	3.8	30		31			″			19			
5	4.8	29		32			″			24			
5	6.4	28		34			″			32			
5	8.4	28		35			″			42			
5	14.4	30		37			″			72			
5	19.4	31		38			″			96			
5	34.8	56		38			″			174			

FIG. 3

In preparing a card such as is shown in Fig. 3 it is assumed that as each group of steps is cut into circuit it will reduce the current by 1/nth of its normal value, where the number of groups is n. By calculating the total ohms in circuit at each required current, and subtracting each total amount from the value succeeding, the resistance of each group of steps is obtained.

It is interesting to note that the negative temperature coefficient of a carbon filament produces a change of resistance which supplements the action of the dimmer, whether the light is being raised or lowered. For instance, let us assume that the carbon filament lamp is burning at half normal candle power and is to be dimmed still lower. If another step of the rheostat resistance is cut into circuit, the current flowing will be reduced, the filament will at once become cooler and will increase in resistance, this increase causing a further slight decrease in the current. Conversely, when any portion of the rheostat is cut out of circuit we have an increase in current which raises the temperature of the filament, and the corresponding decrease in its resistance allows a slightly greater current to pass, just as if another step of the rheostat were cut out of circuit. In this manner, the carbon filament acts to assist the dimmer, step by step through the entire range of control. Of course this action is very slight through most of the range, for the lamp resistance remains practically constant, as already demonstrated.

In striking contrast with this is the tungsten lamp, which opposes every attempt at control, and must be regulated by much finer divisions of resistance to get flickerless dimming. As in the case of the carbon lamp, let us assume half normal candle power and cut additional resistance into circuit to obtain less illumination.

At 110 volts this tungsten lamp gives 36 candle power, and the 18-candle power mark is reached with 91 volts impressed, and 0.317 ampere flowing. (See curves *B* and *C*, Fig. 1). The lamp resistance at this candle power is therefore 287 ohms. The rheostat resistance in series to give this condition on a 110-volt line is obviously 19 ÷ 0.317 = 60 ohms. If the resistance of the lamp filament remained constant, we could reach quarter normal candle power by inserting 39 ohms additional in circuit, or a total rheostat resistance of 99 ohms. These data are taken from curves *B* and *C*, Fig. 1, where it will be noted that nine candle power is emitted at 76 volts with 0.285 ampere flowing. As a matter of fact, however, the lamp resistance at quarter normal candle power is 266 ohms, so that the total rheostat resistance at this point must be 120 ohms instead of 99, or approximately a 50 per cent greater increase than that which would be necessary with a filament of constant resistance. In the same way, when resistance is cut out of circuit, in order to raise the candle power, it must be reduced at a rate which will compensate for the increase of the resistance of the tungsten filament with increasing temperature.

The shape of curve *B*, Fig. 2, indicates that the tungsten filament changes in resistance throughout the entire working range of the lamp, and, furthermore, that the rate of this change is not constant. Curve *B*, Fig. 2, shows this more clearly than curve *C*, Fig. 1. The last-mentioned curve resembles somewhat the parabola $X^2 = 4\,p\,y$, but does not coincide with it.

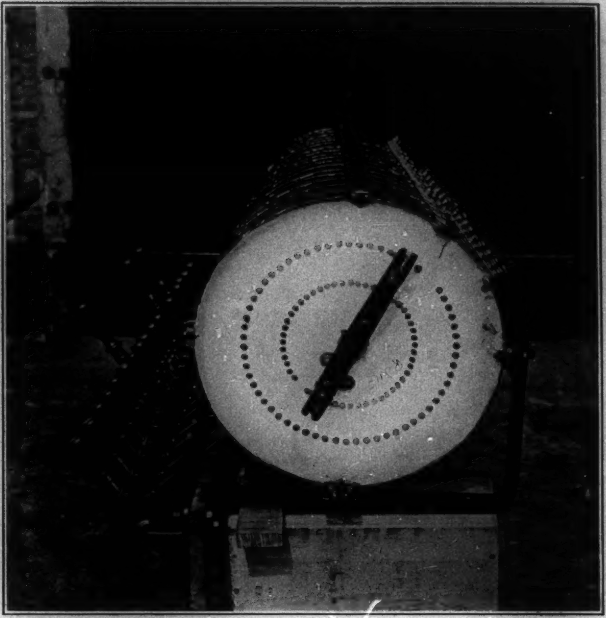
Evidently, when designing a dimmer for controlling this lamp, we shall not be able to assume a constant value for the lamp resistance, as in the previous case.

It would be possible, no doubt, to work out the equation of the curve, and make some interesting deductions by means of it, but by far the most convenient method is to obtain various values of resistance from curve *C*, Fig. 1. By calculating the resistance required in series with the lamp at various voltages, the correct resistance for each group and step is readily obtained.

The marked contrast between this lamp and the carbon filament type is more than ever noticeable when we compare curve *B*, Fig. 2, with curve *A*, Fig. 2. The resistance of the tungsten filament at full incandescence is approximately 16.5 times its cold resistance, while that of the carbon filament at full incandescence is about one-half of its cold resistance. The one-tenth of one candle power mark is reached at 48 volts for the carbon filament, and 28 volts for the tungsten filament. The tungsten filament may be made visible red with 10 volts, while 18 volts are required for the carbon filament.

Now, if we assume a constant line voltage of 110 volts, and a dimmer in series with our lamp, we may obtain from curve *C*, Fig. 1, the amperes flowing when different proportions of the line volts are dropped on the rheostat. Tabulating the results thus obtained we have:

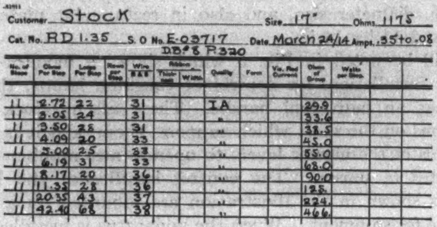
Volts on lamp.	Volts on rheo.	Amperes.	Total rheo. resis.	Increment of resis.	Per cent of total resistance.
110	0	0.355	0		
100	10	0.335	29.9	29.9	2.54
90	20	0.315	63.5	33.6	2.86
80	30	0.295	102.0	38.5	3.28
70	40	0.272	147.0	45.0	3.82
60	50	0.247	202.0	55.0	4.68
50	60	0.222	270.0	68.0	5.79
40	70	0.194	360.0	90.0	7.65
30	80	0.165	485.0	125.0	10.68
20	90	0.127	709.0	224.0	19.05
10	100	0.085	1175.0	466.0	39.60



[WALLER]

FIG. 5—THEATER DIMMER FOR TUNGSTEN LAMPS

After the characteristics of a suitable rheostat had been obtained as above, considerable experimenting was found necessary in order to determine how many steps or subdivisions there should be to a group. Some eyes are more susceptible than others to changes in the intensity of light, and in nearly every case the color and form of the illuminated objects, or the background, will make an appreciable difference. To cover this point thoroughly, a large number of tests was made before a group of witnesses who independently recorded their observations. In the first rheostat constructed, each of the ten groups or increments in the table was divided into 15 steps, this rheostat was compared, and tested with one having a total of 130 steps, another with 120 steps, another with 110 and a fifth with 100 steps. This last rheostat gave very satisfactory control on a 110-volt line, but it was not considered advisable to use a lower number of steps, as several of the witnesses could detect a slight flicker at certain parts of the range when 90 steps were used. It will be remembered that the tungsten filament begins to glow at 10 volts, and if the dimmer is used to cut down the line volts to this point, there will be 110 − 10 = 100 volts impressed upon it, or in other words, a properly designed 100-step dimmer will regulate to approximately one volt per step throughout the range, if used on a 110-volt line. It is not uncommon, however, to find lines which run to 120 volts or slightly over, and for this reason the tungsten dimmer was designed with 10 groups each of 11 steps, or 110 steps total. The values are given in Fig. 4.



Customer Stock Size 17" Ohms 1175

Cat. No. RD 1.35 S. O No. E-03717 Date March 24/14 Amps. .35 to .08

DB#8 P.320

No. of Steps	Ohms Per Step	Loops Per Step	Rows per Step	Wire B&S	Ribbon		Quality	Form	Vis. Red Current	Ohms of Group	Watts per Step		
					Thickness	Width							
11	2.72	22		31			IA			29.9			
11	3.05	24		31			"			33.6			
11	3.50	28		31			"			38.5			
11	4.09	20		33			"			45.0			
11	5.00	25		33			"			55.0			
11	6.19	31		33			"			68.0			
11	8.17	20		36			"			90.0			
11	11.35	28		36			"			125.			
11	20.35	43		37			"			224.			
11	42.40	68		38			"			466.			

FIG. 4

The mechanical design was accomplished by using a circular plate 17 inches in diameter, with two concentric rows of contacts as shown in Fig. 5. The contact shoes mounted on the rheostat arm or lever must be noiseless and very smooth running, for flickering of the lights may be produced by uneven contact. Ease of mechanical movement is essential in work of this kind, for the most carefully designed rheostat will not give satisfactory control if the contacts bind or stick, and the contact arm jerks from point to point as the control lever is moved over.

In most theater installations the dimmers are placed at the top of the switchboard, and, as the number of circuits controlled is sometimes quite large, the size of plate is very important. These 110-step plates may be mounted four inches apart and compare favorably in dimensions with the dimmers for carbon lamps which they are designed to replace. Dimmers for carbon lamps are supplied by well-known manufacturers in 18-in. diameter size, and also in rectangular plates 15 by 24 in. and 14 by 14 in.

It will be noted in Fig. 5, which shows a modern type of dimmer installation, for control of tungsten lamps, that each plate has an individual handle. These all interlock at will with cams on the shaft which supports them, and it is possible by means of the master levers to operate any number or all of the plates in unison. The control handles of the bank of dimmers shown in the illustration are mounted on a wooden template for shipment. When the apparatus is installed on top of a theater switchboard, the bearings of the operating shaft are transferred to the top of the switchboard slate. This makes a convenient and accessible arrangement.

DISCUSSION ON "DIMMERS FOR TUNGSTEN LAMPS" (WALLER), NEW YORK, FEBRUARY 18, 1915.

Leonard Kebler: In Mr. Waller's paper, he refers to the necessity of the contact shoes moving smoothly over the contacts, and also to the necessity for having easy mechanical movement. In designing a dimmer to get proper change in theater lighting, the first requisite is the proper proportioning of the resistance, as described by Mr. Waller. After this is done, the mechanism that actuates the resistance controlling arm, and the friction between the moving arm and the stationary contact, pivots, etc., must be such that the arm can be moved over the contact evenly with a minimum of effort on the part of the operator.

If this mechanism is so made that under operating conditions it sticks until undue force is exerted to move it, the arm will jerk over several contacts and produce the uneven gradation or flickering of light that we are trying to eliminate. This is especially true in theater dimmer mechanism, which is usually installed back of or on top of a switchboard where it is not readily cleaned or oiled, and consequently becomes dirty and even may become clogged by dirt or dust if not properly designed. Poor contact between the stationary and moving contacts may also cause flickering, and must be guarded against. On account of the lack of lubrication encountered in practise, it becomes desirable that the rubbing surfaces of the movable and stationary contacts shall be of dissimilar metals. Such dissimilar metals as brass and copper are useful for this purpose.

The spring pressure that presses the movable contact against the stationary contact should be such that dirt, etc., shall not catch or retard the movement of the moving arm and shall not, in practise, lift the moving contact member off the stationary parts. A form of shoe known as "skate shoe" eliminates these troubles. This shoe is a block of copper pressed against the brass stationary contact by means of two independent spring plungers, located at the two ends of the shoe in the line of travel. The shoe has rounded ends so that it readily slides over obstructions. A copper cable sweated into the shoe and the moving arm carries the current to the arm.

Such a "skate shoe" may have one end lifted an eighth of an inch or more off the contact while the other end still makes good electrical connection. It will travel over any dirt or roughness with the minimum effort applied to move it. At the same time, it is comparatively inexpensive.

The bearing on which the contact lever turns should be long and sturdy, and here again two dissimilar metals for the two bearing surfaces are desirable, so that rust, dirt, or lack of lubrication shall have the minimum effect.

Another important feature is the mechanical connection between the hand-operated arm and the resistance controlling arm. There must be no lost motion in this. It should not need lubrication, and dirt or dust should not clog it or injure its free action in any way.

I should say that a proper theater dimmer specification might well say: "The sliding contact and the driving mechanism must be such that dirt, dust and lack of lubrication, such as is met with in practise, shall not prevent the smooth movement of the sliding contact over the stationary contact, with a practically equal pressure on the operating handle over the complete arc of travel."

Charles D. Knight: The table in the paper giving a total resistance of 1175 ohms indicates that approximately four times the hot tungsten lamp resistance is utilized to dim the lamp to a visible red filament. As there would then be a drop of ten volts across the lamp, the dimmer would, of course, absorb 100 volts when used on a 110-volt circuit.

Further on it is brought out that 100 steps of one volt per step give satisfactory regulation, although because some circuits might be 120 instead of 110 volts, 110 steps are included in the dimmer. The assumption would be that on 120 volts somewhat more resistance would be required than on 110 volts to reach the same dimming point, and therefore, the additional steps would be logical. However, from the table on the same page, which shows the subdivisions for 110 steps, the original total resistance of 1175 ohms is maintained. This is not quite clear, as it would seem to indicate simply finer regulation when divided among 110 steps rather than taking care of any increased drop, which would be the case at 120 volts. It would seem as though nearer 1400 ohms would be desirable to take care of 120-volt lines.

In most instances a dull red filament gives sufficiently low dimming. However, we have noticed that when several borders were running at just visible red filament for each individual lamp, considerable light is diffused, making objects on the stage discernible from the front of the auditorium.

It is desirable at times in obtaining the most realistic effects that the first appearance of light on the stage should not be discernible to the audience. This means that the dimmer must control the lamps from full light to black filament. This is accomplished by including in the dimmer approximately five times the hot resistance of the lamp, or in the case of a 40-watt 110-volt tungsten lamp, 1600 ohms. To take care of 120-volt circuits a series resistance of about 1750 ohms is necessary.

We agree that 100 divisions of resistance will give the proper regulation of tungsten lamps, and that any number below this is prohibitive. Without trespassing greatly upon the value of the figures given, we believe that 100 divisions with approximately equal volts per step will give satisfactory regulation from 5 to 110 volts on the lamp, and with a 120-volt circuit, the additional drop per step is so small as to not be discernible in the dimming of the lamp.

John B. Taylor: Has this figure of one volt per step been determined in any manner other than building a rheostat and seeing that it works? A more exact way would be to see if one volt between 100 and 99, produced more visible effect than one volt between 10 and 11—one volt between 10 and 11 is ten per cent, but naturally, as the filament is colder it cools down more slowly and the percentage change may be greater. It is interesting to know if any work has been done trying one volt at 100 volts, 75 volts and 50 volts, to see if the one-volt step is the best curve to meet the requirements.

Comfort A. Adams: I might suggest in answer to Mr. Taylor's question, that it does not necessarily follow that the gradation of resistance should be that which would give an absolutely uniform rate of change of illumination. The rate of change of illumination may be different in different parts of the range, and still give the desired effect. In fact, I should think that the desirable increase in illumination would be very much smaller in the earlier stages of the change than later.

W. S. Franklin: According to a well-known principle in the psychology of the senses each step in candle power of a dimming lamp should be in proportion to the actual candle power of the lamp at that stage of the dimming process in order to get the maximum smoothness with a given number of steps; or in other words, the successive candle powers of the dimming lamp should constitute a decreasing geometrical progression.

It seems to me that the best way to design the steps of the dimming rheostat would be to take two lamps, side by side, each with a continuously adjustable rheostat in series with it. Beginning with both lamps at the maximum of brightness, dim one lamp until you can just barely perceive the difference in brightness, then dim the other lamp until it is just perceptibily dimmer than the first, and so on. Thus you get a series of proper steps.

H. Ward Leonard: I did not intend to make any comment on this paper. The only thing I could suggest in connection with the remarks which have been made as to the best design of dimmer, is that commercial considerations make it desirable, if possible, to have the dimmer very compact. The best way to get the minimum size in handling a certain duty, is to try to so arrange the constituents that each particular step when working at its maximum duty shall be producing a number of watts which shall be constant for each of the steps under that maximum condition. That is to say, you can make the plate much smaller and avoid undue heating of some steps, or improper cooling, as you might say, on other steps, if the maximum watts per step are made constant when that step is operating at its maximum duty. That is a consideration of great importance, because in theater dimmers the question of space is of very controlling importance in many instances.

It is rather interesting to recall the historical side of the subject. As far as I know, the first interlocking dimmer used in a theater was the one that I installed in Chicago, in 1885, that is just thirty years ago. In those days the dimmers were large boxes of iron wire for the coils, and with a very large switch, composed of a number of different plates with the contacts so arranged that various combinations were obtainable. The dimensions of that theater dimmer, which was installed in McVicker's Theater, in Chicago, I think were probably at least twenty times what would be necessary today; and that is of quite a great deal of importance in the available space that a theater stage represents.

It was necessary under the conditions at that time to mount the coils overhead and have various tooth gears and clutches for securing the interlocking arrangements; but the plate form of rheostat, which is practically universal today, and which has the switching features and the resistance features combined in one plate and these plates arranged in bank, has resulted in an extreme reduction of the dimensions. The various devices for interlocking have also in the course of years been made much more compact and require very much less effort to operate them than was formerly the case.

Alfred E. Waller: I have been much interested to note that in the course of this discussion several points have been brought out that occasioned a good deal of thinking when the design of this dimmer was originally under consideration. The problem is one which is rather embarrassing, if you try to attack it from the purely theoretical standpoint. In his address last night, Dr. Humphreys said that all electrical engineering problems could not be satisfactorily solved by mathematics alone; and this, I believe, is one of them. I think, very naturally, the tendency of every engineer is to try to figure it out; but this problem involves a variable, namely, the eyes of observers. A suggestion was made that possibly good results might be obtained by placing two lamps side by side and dimming one, so that it was always slightly dimmer than the other, and regulating the steps of the rheostat in that way. That was tried, but it was found very difficult, particularly where the lamp was near full candle power; because if you start two lamps at full candle power and dim one until you can notice it, you will find if you place these lamps out of sight and regulate the voltage across them in such a way that a corresponding change in illumination is obtained, throwing the light on a background to eliminate dazzle, that you will be able to see the flicker.

One way in which the one volt difference was arbitrarily fixed, was to connect a lamp in a circuit, the potential of which could be varied one volt up and down with great rapidity, or, in fact, any number of cycles per second. We found when that change was a one-volt change, that the change in illumination was imperceptible; but when we began to increase that change in potential across the lamp, we got an effect that was comparable to that which is obtained when you connect a tungsten lamp on a 25-cycle circuit. We had to limit ourselves in studying the changes of illumination to the maximum allowable change of illumination and the effect of this change of illumination on a background, and we selected a number of backgrounds. This method eliminates the dazzle, and gives better results than direct inspection of the filaments.

It is easy to see, if you look at the curve, that the rate of change of illumination varies, if the dimmer contact arm travels at a constant speed; because one volt at a certain part of that range will give us a greater change in candle power than it will at other parts of the range. This in practise is not noticed at all, because hand-operated dimmers in particular are generally moved just enough to get a certain effect. If a man wishes to change the candle power at a constant rate, as for instance, in a sunrise effect, it would be necessary to move the dimmer contact arm a little bit slower during the first part of the range than during the latter part.

I fully agree with Mr. Knight that less than 100 steps is not advisable in a dimmer of this type.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 18, 1915, under the auspices of the Committee on Use of Electricity in Marine Work.

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SEARCHLIGHTS

BY C. S. McDOWELL

Abstract of Paper

Searchlights have remained practically the same for the past 25 years, although there is great necessity of an improved searchlight on account of the increased range of torpedoes and increased speed of torpedo boats.

The constituent parts of a searchlight are given in the paper and some of the essential and desirable features of the various parts are shown. Methods of testing searchlight mirrors are given, with illustrative figures.

The results of tests conducted on Navy standard 36-in. and 60-in. searchlights and Beck 44-in. searchlight show the latter type to be much more efficient in illuminating distant objects. Relative results are shown in the figures.

SEARCHLIGHTS were first used during the Civil War in a very crude state; these first searchlights were fitted with metal mirrors. Later, Fresnel lenses were used to concentrate the beam. In 1876, the Mangin type of mirror was first brought out and in 1886, Schuckert, in Nuremburg, succeeded in producing a glass parabolic mirror ground to mathematical accuracy. Practically no changes have been made since that time to increase the efficiency of the searchlight; some mechanical improvements have been made, and methods of manufacture of carbons perfected, but practically the ordinary searchlight of to-day is the same as that of 25 years ago.

In view of the increasing speed of torpedo boat destroyers and the increased range of torpedoes, it is very important that the searchlight, one of the principal means of defence against night attack, should be improved if possible. There has lately been developed by Mr. Heinrich Beck of Germany a new type of searchlight much more efficient than those now in use, which is described a little later in this paper.

In considering the question of searchlights and their relative efficiencies, it becomes natural to consider them as made up of the following constituent parts:

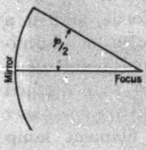
1. Searchlight drum, pedestal, system of control in azimuth and in elevation, shutters and other purely mechanical details.
2. Rheostats.
3. Searchlight mirror.
4. Lamp mechanism.
5. Searchlight arc.

One type of searchlight may show increased efficiency over another because some of these parts have been worked out to give the very best results, but a searchlight to give the very best results must have all these details worked out separately and then joined together in the proper relation to give the maximum efficiencies.

Searchlight drum and other mechanical details are questions of design which affect the efficiency of the light very little. They should be worked out carefully, however, so that the searchlight is properly balanced, may be easily trained in azimuth and elevation from a distant control station or at the light itself. The drum should be so made that air currents cannot be set up inside, thereby causing flickering of the arc; ventilation should be sufficient so that light may be kept on at full intensity with shutter closed, or other means adopted for keeping the light burning at lower intensities with shutter closed and bringing it to full intensity instantly upon opening of shutter. It is also considered advantageous to have a permanent ammeter and voltmeter mounted on the searchlight drum, or a connection on it so that portable instruments can be connected. A ground-glass finder which shows the position of the arc, the arc length, and the variations of the positive crater from the focus of the mirror is considered an essential in a properly designed searchlight. The mirror should be so secured that it may be readily removed and the mirror and front door strips should be mounted in such a manner as to eliminate shock and breakage.

The rheostat used in connection with searchlights consists of two parts: a fixed and a variable resistance. A certain amount of fixed resistance is necessary to overcome the natural instability of a carbon arc and its value must be at least sufficient to give a voltage drop in the resistance equal to one-half the arc stream voltage. The variable resistance is necessary in order to obtain the proper arc voltages for various carbons and various lengths of line. The resistance elements must be of sufficient area to carry the maximum currents used without undue heating of any parts and of such material that the resistance does not change excessively with temperature changes. The steps should be not greater than one volt each.

The efficiency of a searchlight mirror depends upon its trueness to parabolic form, its trueness of surface grinding, the color and structure of the glass, and the thickness of the glass. The losses in searchlight mirrors are due to stray rays outside of the conical beam and to absorption in the mirror. The intensity of illumination on a distant object, provided equal amounts of light fall on the mirror, is dependent on the efficiency of the mirror and the angle of dispersion (that is, at a distance, the area of the illuminated plane normal to beam).



The relation between the focal length and diameter of the mirror should be such that the effective angle φ should include the majority of light given off by the arc. By increasing the focal length, the diameter of mirror remaining constant, the ratio of the light falling on the mirror to the total given out by the arc is decreased but also the angle of dispersion is decreased, therefore, the correct focal length is that which, changed in either direction, decreases the foot-candle illumination on a distant object. If we increase the diameter of the mirror at the same time as the focal length is increased, the angle φ can be maintained constant and at the same time the dispersion decreased, thus giving greater intensity of illumination on a distant object. On board ship, however, the size of the searchlight and thus the diameter of the mirror is limited. A greater focal length is also of advantage in that it takes the arc farther from the mirror and thus decreases the chances of breakage of the mirror due to the heat of the arc.

In determining the efficiencies of searchlight mirrors, various tests are carried out:

(*a*) *The Line or Screen Test.* If we imagine a section taken through the center of the mirror, a curve is obtained whose curvature should vary in a regular manner from the center towards the edge, but the curve will take a wavy form instead if the surface has not been accurately ground.

The mirror is erected opposite a screen on which are painted two systems of parallel straight lines at right angles to one another. The image of these lines is photographed by a camera placed back of the hole in the center of the screen. If both surfaces of the mirror are properly ground the lines in the photograph should be regular but not necessarily straight nor parallel. This test does not show if the mirror is parabolic or not.

An illustration of a mirror showing this test is given in Fig. 1.

(*b*) *The Sun or Zone Test.* A perfect mirror should reflect rays from a point of light situated at its focus, in parallel straight lines. It must, therefore, also have the property of bringing a parallel beam of light, as from the sun, to a focus in a single point. This as made, consists in placing the mirrors in a plane perpendicular to the sun's rays and photographing the reflected focal point, brought out in contrast by blowing smoke on it.

An illustration of this test is shown in Fig. 2.

(*c*) *Beam Photometric Tests.* It is considered that the most reliable test of mirrors is actually to mount them in a searchlight, place a constant source of light in the focus, and at a standard distance measure the actual foot-candles of illumination throughout the entire beam. The focal point of a mirror to be tested is first accurately obtained (our method being to place two mirrors exactly parallel with each other about 30 ft. apart and place a concentrated filament lamp approximately at the focal point of the second and measure accurately the focal length of the first); the mirror under test is then mounted in a searchlight frame held in a fixed position, a concentrated filament lamp placed accurately in the focus (a 50-watt lamp is used) and at a standard distance measure the foot-candles by a portable photometer. These foot-candle readings are usually obtained every four inches across the beam on two lines perpendicular to each other and passing through the center. For the larger size mirrors 200 feet has been taken as the standard distance. Curves obtained in this test are shown in Fig. 3.

By calculating the amount of light flux falling on the mirror and that received on the distant object the losses in the mirror may be found and the coefficient of reflection obtained.

In a number of cases, mirrors which showed nearly perfect grinding and sharp focal point, as determined by the first two tests, were found on this third test to reflect less light than other mirrors which had shown much poorer results on the screen and zone tests.

The lamp mechanism of a searchlight should be such as to

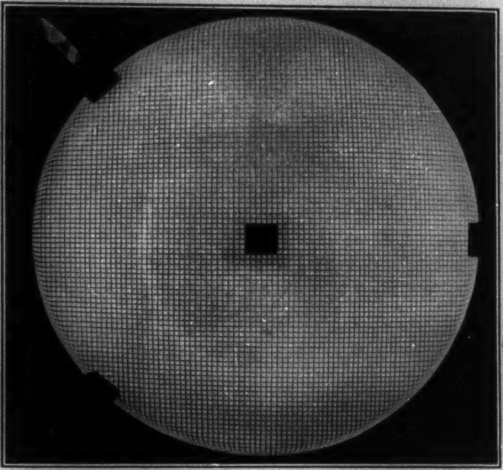


FIG. 1 [MCDOWELL]

FIG. 2 [MCDOWELL]

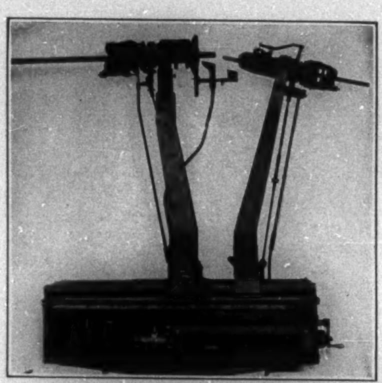


FIG. 4 [MCDOWELL]

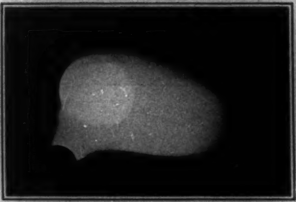


FIG. 7 [MCDOWELL]

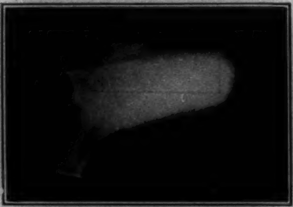


FIG. 8 [MCDOWELL]

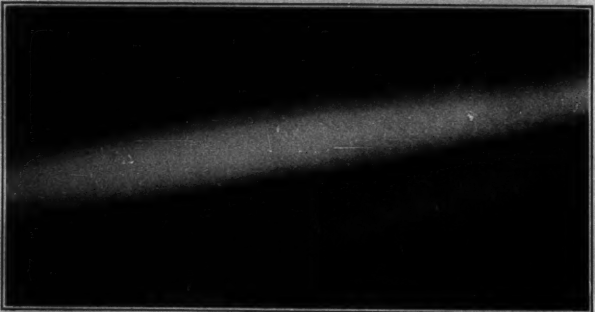


FIG. 9 [MCDOWELL]

keep the crater of the positive carbon at the focus of the mirror, should keep the arc length that which is desired, should carry the current of the carbons, should contain mechanism for rotating at least the positive carbons, should be sufficiently rigid to keep the carbons in proper alignment, and should require little care and adjustment.

An illustration of the Beck lamp mechanism is shown in Fig. 4. Both carbons are rotated for the purpose of keeping surfaces bathed in the inert gas and to keep the arc central and thus promote evenness of burning. The positive holder is fixed, the carbon being fed through it at such a rate that the crater is always maintained at the focus of the mirror; the rate of feed is controlled automatically, a small mirror being placed in the drum which, when the carbon feeds too slowly, reflects a small beam on a thermocouple, and closes a relay circuit which by means of a solenoid quickens the feed. When the carbon is back in focus the small beam of light is off the thermocouple and the feed is slowed down. In addition, the feed may be controlled by hand. The negative carbon feeds through the negative holder in a similar manner, except that the control is by hand. The negative holder is also fixed except when striking the arc, when it is moved up by a striking motor.

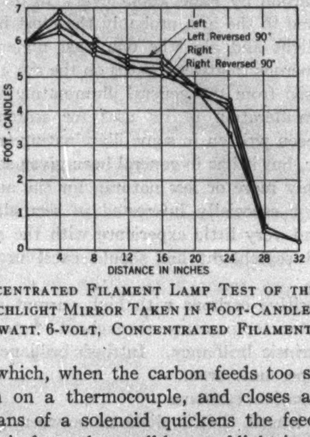


FIG. 3—CONCENTRATED FILAMENT LAMP TEST OF THE NAVY STANDARD 36-IN. SEARCHLIGHT MIRROR TAKEN IN FOOT-CANDLES AT A DISTANCE OF 200 FT.—50-WATT. 6-VOLT, CONCENTRATED FILAMENT LAMP USED

During tests recently conducted on searchlights, the Beck lamp mechanism functioned very satisfactorily; variation of the crater of the positive carbon from the focus was about 1 mm. (hardly noticeable) and the arc length was kept practically constant. No trouble in maintaining the arc was experienced while rotating both carbons, the crater of the positive carbon remained even and there was no noticeable hissing and jumping of the arc. On the other hand, while the standard motor-controlled lamp mechanism functioned successfully, maintaining practically a constant voltage, the arc length did not remain constant and the positive crater did not remain at the focus, due to the impracticability of constructing positive and negative carbons which will be consumed at a certain given ratio. Also the positive crater tended to wander over the surface of the positive carbon with the result that one side would project and the other recede, causing a hissing arc and making it necessary, in order to obtain any consistent results, to shut off the light and turn the positive carbon by hand about every 15 or 20 minutes.

We now come to the arc, probably the most important part of the searchlight and also the one least understood. There have been numerous treatises written on the arc, but it has been always discussed from the general illuminating side and without much consideration of its uses for searchlights. Paragraphs have been written in some illuminating treatises on the searchlight arc, but it has in general been given scant attention. This is probably more or less natural, for the authors of these books were not especially interested in searchlights, and, as a rule, had had very little experience with the subject.

The desired searchlight arc should excel in the following particulars:

1. Small positive carbons with high current densities and thus high crater temperature throughout crater area, which gives high intrinsic brilliancy. Intrinsic brilliancy is the luminous intensity per unit area.

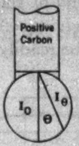
2. Small negative carbons.

3. Long arc length, that is, distance between positive crater and negative point.

4. Uniform mixture of carbon so as to help the evenness of burning.

The Beck searchlight may be considered as being especially designed to meet the above requirements and therein lies its marked superiority over the searchlights now in use.

In a searchlight the angle of dispersion is directly dependent on the diameter of the source of illumination, provided the focal length is constant, and if the diameter of the source could be decreased one-half while the candle power remains constant, the intensity of light on the target would be quadrupled. Actually, in the Beck light, the positive carbon is reduced one-half and at the same time the candle power is increased so that greater efficiencies are obtained.



To illustrate the effect of arc length on candle power it may be stated that with a circular plane radiator (the crater of the positive carbon approximates such a radiator) the maximum candle power is obtained on the vertical axis of the radiator, as shown by the sketch. Here we have I_0 = maximum intensity, and $I_\theta = I_0 \cos \theta$. Thus the smaller the angle the greater the maximum intensity of light falling on the mirror. With positive and negative carbons of a fixed diameter the angle θ depends upon the arc length, being the angle of partial shadow on the mirror projected by the negative carbon cutting off through this angle the light rays emitted by the positive carbon. This may be more clearly expressed by the formula

$I_\theta = I_0 \, q \cos \theta$, where I_0 = the normal intensity as before,

I_θ = the intensity at any angle θ from the normal, and

$q = \dfrac{\pi r^2 - S}{\pi r^2}$ where r = radius of positive carbon and

S = the area of overlap of the negative on the positive for the angle θ.

The light intensity is reduced by the shadow of the negative carbon only for those angles of θ which are smaller than

$\tan \theta = \dfrac{r + r_1}{l}$, where

r = radius of positive carbon,
r_1 = radius of negative carbon,
l = arc length.

Thus it is seen that to decrease the angle of shadow it is necessary to increase arc length or decrease the diameter of negative carbon. The arc length is restricted to the stability point of burning.

In Fig. 5 is shown by curve the increase of candle power with increase of arc length; the candle powers are taken at 40 deg. from the normal to arc surface and are approximately the maximum.

The arc length of the Beck lamp is maintained constant at about $\frac{7}{8}$ in. as compared to about $\frac{5}{8}$ in. obtained at 60 volts in the standard 36-in. lamp.

Fig. 6 shows the variation of arc voltage with arc length as determined on a set of ordinary 36-in. carbons with constant current of 110 amperes.

It is, of course, well known that carbon is the most refractory of all known materials, boiling at about 4000 deg. cent., but it unfortunately commences to evaporate at a much lower temperature (about 1800 deg. cent.), so that in an ordinary arc very little of the total area of the end of the positive carbon is at the melting temperature, a small wandering spot being the real efficient part of the carbon, and the rest of the end of the carbon is consumed at a much lower temperature, giving off less intense rays and a longer wave length. This may be readily seen in comparison of the Beck and ordinary arc by the color of the arc.

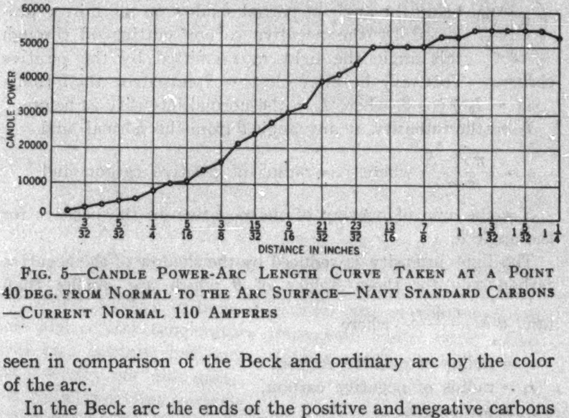


Fig. 5—Candle Power-Arc Length Curve Taken at a Point 40 deg. from Normal to the Arc Surface—Navy Standard Carbons —Current Normal 110 Amperes

In the Beck arc the ends of the positive and negative carbons are enveloped in the hydrocarbon vapor which prevents the consumption of the carbons at a lower temperature, by keeping oxygen from them; in addition it cools the outer shell of the carbons, the gas being at a temperature of about 1000 deg. cent., and thus concentrates the current in the center of the carbons. Thus a current density greater than 0.75 ampere per sq. mm. is obtained, and the total crater of the positive carbon reaches a very high temperature. The current is brought to both carbons near the ends by roller contacts, so the only part having this high current density is the part protected by the indifferent gas. The positive carbon is cored with a rare earth with a melting point at about 3500 deg. cent. The positive develops a deep crater, about 12 mm. deep, filled with incandescent gas. The sides of this crater reflect the light radiation to the focus of this crater and in addition, the light from the negative is reflected, so it is believed nearly true black body radiation is obtained; and by adjusting the focus of the crater to focal point of the mirror the high peak in the luminosity curve of the beam is thus accounted for.

The area of the Beck positive carbon is 201 sq. mm., the area of the ordinary 36-in. light positive carbon is 805 sq. mm. In the Beck light the maximum intrinsic brilliancy is greater than 438 c.p. per sq. mm. The intrinsic brilliancy of an ordinary carbon arc varies from 120 c.p. per sq. mm. to 160 c.p. per sq.mm.

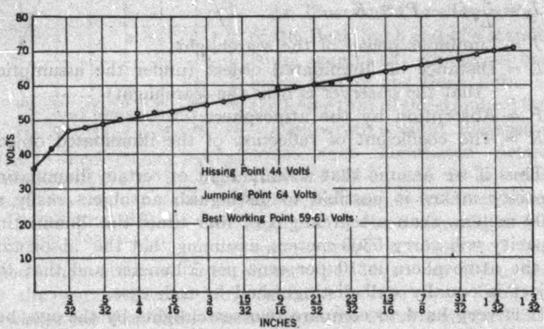


FIG. 6—ARC VOLTAGE-ARC LENGTH CURVE—NAVY STANDARD CARBONS USED—LINE CURRENT CONSTANT AT 110 AMPERES

In addition to the black body radiation obtained from the crater, there is evidently a large amount of light radiated from the incandescent gas in the crater, of a selective nature. It would probably at first be thought that this gas should follow Kirchhoff's laws and absorb the lines which they naturally radiated, giving the Fraunhofer lines seen in the sun's spectrum, but in this case the incandescent gas is at a higher temperature than the crater and the spectrum shows positive lines apparently superimposed on the regular temperature radiation.

It is noticed that, taking the Beck carbons and starting at a low current density, a luminous arc stream as of a typical white flame arc is obtained, the anode being convex. As the current density is increased the anode becomes concave and the anode stream disappears, apparently being confined to the crater of the positive carbon, leaving only the lower temperature and less luminous cathode stream. The temperature of the incandescent gas within the positive crater is estimated to be between 5000 and 5500 deg. cent. Two views of the Beck carbons burning with normal current densities are shown in the illustrations, Figs. 7 and 8.

For the luminous power J_l, which reaches the eye of the observer, we have the following equation:

$$J_l = \frac{J}{L^4}(1 - P)^n K$$

J = Luminous power of the searchlight.

L = Distance of illuminated object (under the assumption that the observer is near the searchlight).

P = Absorption by the atmosphere.

K = The coefficient of reflection of the illuminated object.

Thus if we assume that a searchlight of certain illuminating capacity makes it possible to distinguish an object easily at 4000 meters, than a searchlight of four times the illuminating capacity will carry 5300 meters, assuming that the absorption of the atmosphere is 10 per cent per kilometer and that the object is equally well distinguished in each case.

It is very hard to compare two searchlights by the eye, but during the test conducted, both searchlights were lighted (Beck and Navy 36-in.) and first one and then the other was turned on the same object with the result that objects not distinguishable, except in a hazy way, with the Navy 36-in. were plainly outlined by the Beck light. It is apparent to the eye that the Beck light is more of a bluish-white light than the standard; the ordinary searchlight beam looks yellow in comparison. The aggregate quantity of blue and violet rays in the Beck beam is about 23 per cent. At low intensities of illumination the maximum sensation to the eye for the same strengths of illumination shifts toward the blue end of the spectrum, while at higher intensities of illumination the maximum sensation for the same strengths is toward the yellow part of the spectrum. This shifting of the relative sensations for different intensities of illumination is a well-known phenomenon called the Purkinje effect. It is thus seen that the Beck light is particularly good for picking up distant objects where the illuminative intensity would be small.

It is also a well-known fact that a colored body reflects the colors from the rays falling on it which the body itself contains, and absorbs the rays which it does not contain; the Beck light being strong in the short waves of light would thus be particularly effective in picking up objects of a bluish color, such as the various classes of ships painted bluish gray.

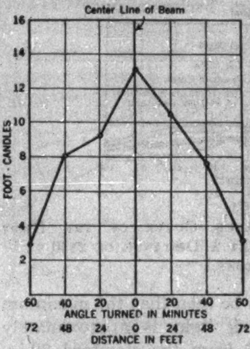


Fig. 10—Foot-Candle Power-Distance Curve of the Beck 44-in. Searchlight taken at a Distance of 2850 ft.—Lamp Burning Normally

An illustration is shown, Fig. 9, of the Beck light and of a standard 36-in. searchlight, the upper beam being that of the Beck light and the lower that of the standard light.

Comparative night illumination tests were conducted between standard 36-in. and 60-in. searchlights and the 44-in. Beck searchlight. The Beck searchlight beam was a more concentrated beam than that obtained from either the 36-in. or 60-in. beam of the standard lamp and the color of the Beck beam was a whiter one than that obtained from the Navy standard 36-in. and 60-in. searchlights. With the carbons burning in a normal condition and placed in the proper focal centers of their respective mirrors, foot-candle-power readings at intervals of 24 ft. were

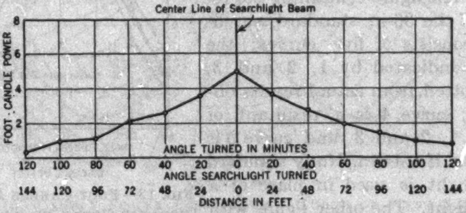


Fig. 11—Foot-Candle Power-Distance Curve of the Navy Standard 60-in. Searchlight taken at a Distance of 2850 ft.—Lamp Burning under Normal Conditions

taken across the beam at a distance of 2850 ft. from the searchlights. Figs. 10 and 11 show the illumination across the beam of the Beck searchlight compared with the 60-in. standard searchlight. From these two curves it can be seen that the maximum illumination obtained from the Beck light is approximately 2½ times as great as that obtained from the standard 60-in. In the Beck searchlight the beam shows a very high illumination at the center and falls off very rapidly at the edge of the beam. The other figures, 12 and 13, were obtained in comparing the Navy standard 36-in. searchlight with the Beck light. The figure containing the results of the 36-in. standard searchlight consists of five curves; the curves indicated by 1, 2 and 3, are plotted from actual results obtained; curve 4 is a resultant of curves 1, 2 and 3, and curve 5 is obtained if a 44-in. Navy standard searchlight is used in place of a 36-in. light. The other figure with the results obtained from the Beck light contains four curves; three plotted from the actual results obtained, and curve 4 is the resultant curve of these three. From the comparative data obtained, it can be seen that the illumination obtained with the Beck searchlight is about five times as great as that obtained from

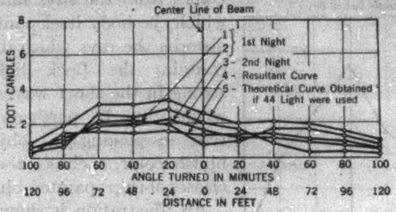


Fig. 12—Foot-Candle Power-Distance Curve of the Navy Standard 36-in. Searchlight Taken at a Distance of 2850 ft.—Lamp Burning under Normal Conditions

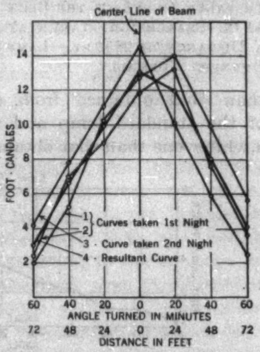


Fig. 13—Foot-Candle Power-Distance Curve of the Beck 44-in. Searchlight Taken at a Distance of 2850 ft.—Lamp Burning under Normal Conditions

the standard light. The spherical candle power of the Beck arc was measured and the results obtained are shown in Fig. 14. The maximum candle power obtained with the use of our present Navy standard carbons is 45,000 candle power, as against 88,000 candle power obtained from the Beck lamp. A zonal candle power curve of standard 36-in. carbon arc with arc voltage at 60 volts is shown in Fig. 15.

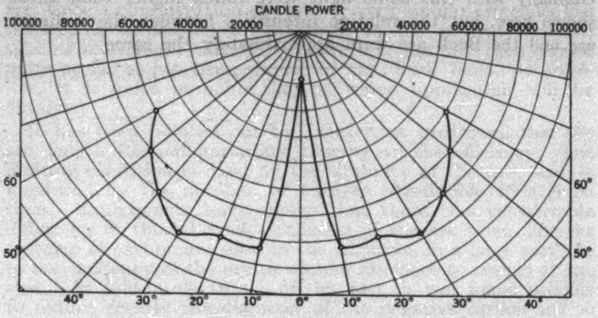


FIG. 14—CANDLE POWER DISTRIBUTION CURVE FOR THE BECK SEARCH-LIGHT LAMP

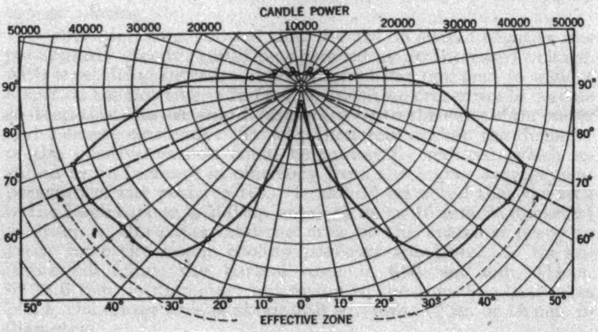


FIG. 15—CANDLE POWER DISTRIBUTION CURVE OF NAVY STANDARD CARBONS—LINE CURRENT 110 AMPERES—ARC VOLTAGE 60 VOLTS—ARC LENGTH CONSTANT AT 19/32 IN.

The results shown in Figs. 10, 11, and 13, are relative only, and cannot be used to determine the zonal candle power of the beam reflected from the mirror. The absorption of the atmosphere would have to be taken into consideration to obtain the actual candle power of the beam; the results obtained in Germany with this same light were much higher than those shown here, but the relative intensities between the ordinary arc and the Beck arc were approximately the same.

DISCUSSION ON "SEARCHLIGHTS" (MCDOWELL), NEW YORK, FEBRUARY 18, 1915.

R. B. Chillas, Jr. (by letter): In taking up the discussion of this paper, it is particularly worthy of note that the author has brought out the desirable characteristics of the searchlight arc, since a consideration of these or very similar principles has resulted in a decided improvement in the present standard type of searchlight carbons. While this has not been carried quite so far as has been shown in the Beck lamp, nevertheless, it is quite probable that a wider application will be obtained.

It has been pointed out by Lieutenant McDowell that the arc length has an important bearing on the efficiency. The limiting condition is fixed by the stability of the arc, and is measured by the number of outages permissible in a given time. Experiments have shown that there is a considerable difference in the inherent steadiness of the arc when different textures of carbon are used in the negative, in a large part due to the tendency of the arc to wander about or to remain at one spot. In taking advantage of this fact, it was found possible to reduce greatly the diameter of the negative carbon and to effect a still further improvement by selecting such a size as would tend to burn with a slightly tapering, rather than a blunt tip. The necessary current carrying capacity is secured by copper plating.

Observation then showed that the arc on such a negative was particularly steady, could be operated at an increased voltage, with a resulting increase in length, and did not tend to wander about on the positive. In fact, the positive crater would become so deep that the arc would finally travel to the sides of the crater and become unsteady. It was then found that the diameter of the positive carbon could be materially reduced, which resulted in an increase in efficiency from the higher average temperature of the positive tip. It should be noted that the area of the Beck carbon is 200 sq. mm. ($\frac{5}{8}$ in. or 16 mm. in diameter) as given in the paper, and the area of the crater is nearly as great since the vapor cooling prevents spindling. In the imimproved trims the carbon area is 650 sq. mm. ($1\frac{1}{8}$ in. or 28.6 mm. in diameter) but owing to the spindling that takes place, the crater area is about 280 sq. mm. ($\frac{3}{4}$ in. or 19 mm. in diameter).

These changes have resulted in improvement in the direction of the first three characteristics mentioned in the paper, namely, an increased arc length, due to the higher arc voltage, with a resulting increase in the energy concentration at the positive crater; a decrease in the shading of the crater by the negative, and a decrease in the tendency of the arc to wander about on the positive, thus maintaining the crater more nearly at the focus. Incidentally, it is found that the light rises rapidly to full candle power, upon starting.

The fourth characteristic, uniformity of carbon, brings up the important question of the relative rates of consumption of the positive and negative carbons, or burning ratio. With carbons selected to fulfill the above characteristics, it is found that there is a certain average natural ratio of consumption in the carbons for each different curve.

Deviation from this ratio must of course be expected, following the probability curve. In the Beck lamp, the automatic focusing mechanism takes care of these variations and keeps the positive crater in position, regardless of the rate of consumption. The operator, of course, must give his attention to feeding the negative at very frequent intervals. In the lamp mechanisms having a fixed feeding ratio, the natural deviations from the average burning ratio results in a movement of the positive crater from the focus, so that the operator must shift the whole lamp mechanism backward or forward in the drum. The importance of having the feeding ratio of lamps of this type the same as the burning ratio of the most efficient carbons cannot be too strongly emphasized. Any changes in the carbons, necessary to cause them to burn in focus must be paid for by a decrease in efficiency, a feature which has caused a great deal of poor operation in the past. It is suggested that in lamps of the fixed feeding ratio type, a set of three change gears be incorporated in the design of the lamp, so that approximately a ten per cent variation either way in the feeding ratio may be made by shifting an idler gear.

As an illustration of the nature of the changes that have been made in the carbons for the different currents, the following tables give the comparative sizes:

SEARCHLIGHT CARBONS

TABLE I—PRESENT SIZES.

Size of mirror	Rated current amperes	Arc voltage	Carbon dimensions		Lamp feeding-ratio
			Positive	Negative	
9 in. (23 cm.)	10	45	½ x 5-1/2 in. (13 x 140 mm.)	7/16 x 3-1/2 in. 11 x 90 mm.)	1.65 to 1
13 in. (33 cm.)	20	45	5/8 x 6 in. (16 x 152 mm.)	1/2 x 4-1/2 in. (13 x 115 mm.)	"
18 in. (45 cm.)	35	45	13/16 x 8-1/2 in.) (20.6 x 215 mm.)	5/8 x 5 in. (16 x 127 mm.)	"
24 in. (60 cm.)	50	48	1 x 12 in. 25.4 x 305 mm.)	3/4 x 7 in. (19 x 178 mm.)	"
30 in. (76 cm.)	80	50	1-1/8 x 12 in. (28.6 x 305 mm.)	7/8 x 7 in. (22 x 178 mm.)	"
36 in. (91 cm.)	120	60	1-1/4 x 12 in. (32 x 305 mm.)	1 x 7 in. (25.4 x 178 mm.)	"
60 in. (152 cm.)	200	65	2 x 15 in. (51 x 380 mm.)	1-3/8 x 12 in. (35 x 305 mm.)	"

TABLE II.—IMPROVED SIZES.

Size of mirror	Rated current amperes	Arc voltage	Carbon dimensions		Lamp feeding-ratio
			Positive	Negative	
9 in. (23 cm.)	10	46–49	0.51 x 4.75 in. (13 x 120 mm.)	0.31 x 4.37 in. (8 x 110 mm.)	1 to 1
13 in. (33 cm.)	20	48–51	0.63 x 5.5 in. (16 x 140 mm.)	0.35 x 5 in. (9 x 130 mm.)	"
18 in. (45 cm.)	35	50–54	0.63 x 7 in. 16 x 180 mm.)	0.35 x 6.25 in. (9 x 160 mm.)	"
24 in. (60 cm.)	50	50–54	0.75 x 10 in. (19 x 250 mm.)	0.39 x 9 in. (10 x 230 mm.)	"
30 in. (76 cm.)	80	55–59	0.97 x 10 in. (25 x 250 mm.)	0.45 x 9 in. (11.5 x 230 mm.)	"
36 in. (91 cm.)	120	58–62	1.12 x 10 in. (28.5 x 250 mm.)	0.51 x 9 in. (13 x 230 mm.)	"
60 in. (152 cm.)	200	65–72	1.37 x 15 in. (35 x 380 mm.)	0.63 x 12 in. (16 x 300 mm.)	1.35 to 1

It should be observed that a material decrease has been made in the cross-section of the corresponding carbons. Also that the new trims are adapted to the present type of lamp, provided the feeding ratio is changed.

Candle power measurements of the new trims show about a 30 per cent improvement over the present standard trim in effective flux on the mirror, together with a greatly improved steadiness and quality of beam. In obtaining these figures, the method used was as follows: An integrating sphere photometer, divided vertically into two hemispheres was used, together with a high candle power incandescent lamp as an auxiliary standard. This lamp was mounted in a metal reflector so that all of the light would be delivered in one hemisphere. First, determine the mean spherical candle power of the auxiliary standard lamp in the sphere; second, remove the rear half of the sphere, mount this lamp so that its entire flux falls within the hemisphere and read the photometer. Third, place the searchlight lamp on the horizontal axis of the hemisphere, with the positive crater at such a distance from the rim that the solid angle subtended by the rim is the same as that subtended by the mirror, and read the photometer. For these readings, namely, the total flux from the auxiliary standard lamp, the illumination produced by it on the hemispherical surface, and the illumination produced by the searchlight on the same surface, the total effective flux in the solid angle θ subtended by the mirror may be calculated,

$$\text{Effective mean spherical c. p. of searchlight} = \text{mean spherical c. p. of standard lamp} \times \frac{\text{(illumination from searchlight)}}{\text{(illumination from standard)}}$$

This affords a very convenient and rapid method for determining the candle power; the values given by this equation are in terms of mean spherical candle power falling on the mirror, that may be converted to mean effective intensity in the direction of the mirror by multiplying by the factor $\frac{2}{1-\cos\frac{\theta}{2}}$ the ratio of a total sphere area to that within the effective solid angle θ.

Several questions have arisen to which we would be pleased to have replies, namely, the normal volts and amperes, and rate of consumption of the Beck carbon. Are the mirrors ground to a parabola on both faces, and to what extent does a departure of the crater from the focus cause a noticeable effect in the beam.

Karl Georg Frank: Schuckert is not the only man to whom credit should be given for the parabolic mirror for the searchlight, but it was Professor Munker, in Nuremberg, who did the theoretical calculations and he and Schuckert worked together, thus being able to manufacture and put on the market the best searchlight mirror that is obtainable. Everybody who has ever used these mirrors, knows of their one special feature, and that is the quality and uniformity of the product. It is not very difficult for any optical man to get a good parabolic mirror once in a while, but to get a parabolic mirror of first-class quality all the time, that is the secret, and it is very difficult to obtain.

I am very glad to see that the searchlight has joined that class of apparatus which in recent years has contributed so much to the use of electricity in the army and navy, and it is aptly said in the paper, that for a period of twenty-five years no special progress has been made in the matter of searchlights. I believe Mr. Beck's achievement is very creditable, and there is really shown a tendency toward further improvement.

The author speaks of the lamp mechanism, and there seems to be some doubt expressed as to whether that is fully reliable and comes up to the requirements which the navy must maintain. Reliability is, of course, of first importance, and it would be interesting to know whether or not those difficulties of which the author speaks, have been overcome.

The author speaks further of the temperature and mentions that carbon evaporates at about 1800 deg. cent. I do not think that figure is correct. The phenomena which occur in an electric arc, are not only thermal phenomena, but electrothermal, and if the carbon is heated up to 1800 deg. cent., without an arc being formed, then I do not think any evaporation takes place at all. It is very likely that a peculiar phenomenon takes place in connection with the ionization of the atmosphere so that little particles of carbon are separated from the carbon and are thrown with the electrons across the space to form the arc. Therefore, I think the figure of 1800 deg. cent. is not correct.

I wish to call special attention to the very interesting treatise by Professor Lummer, of Breslau who recently measured quite correctly the temperature of the arc and has produced arcs under pressure as high as 22 atmospheres, and he obtained temperatures up to 6000 deg. cent. It seems to me, also, that the special value of Mr. Beck's achievement lies in obtaining this high temperature which Mr. McDowell gives as about 5000 deg. cent. It is, in my opinion, impossible to obtain the same effect by any other means. The previous speaker pointed out some tests and experiments made in this country, and in connection with that I wish to say that a foreign company made similar tests and changed the size of the carbon, and also the density of the current in the carbon. For instance, the Argentine battleships built in this country have been equipped with foreign searchlights, and as far as I remember the size of the carbons has been changed and negative carbons of smaller size, say 38 mm. to 40 mm. diameter, were used.

But, according to what we know today, it is not possible to obtain such a high efficiency as, for instance, Mr. Beck obtains, by the other process, because it is not possible to obtain such a high temperature. It is well known that the intrinsic brilliancy of the arc and of the crater does not increase proportionally with the current. If you exceed a certain current density you will not get a proportional amount of increase in efficiency and intrinsic brilliancy.

Then I wish to call attention to the statement in the next to the last paragraph, which is very interesting. It is said that the increase of illuminating capacity of four times makes it possible to increase the radius of action, so to speak, from 4000 meters to 5300 meters. You see therefore, that even an increase of about 400 per cent in the illuminating capacity brings about an increase of only 33 per cent in efficiency. That further points out the importance of the absorption of the light in the atmosphere.

I want to point out that the possibility of discerning a distant object is, as the author also said, dependent first of all on the quality of light received by the object, second, on the nature of the surface illuminated, particularly its color and reflecting properties; third, on the transparency of the atmosphere, and fourth, on the nature of the objects surrounding that atmosphere. Under ordinary conditions, with a 90-cm. searchlight you can figure on a radius of action of about one mile, or a little less, but, as mentioned before, it is very dependent upon the atmosphere, because the absorption of the atmosphere varies between 2 and 50 per cent and if dense fog is present, of course, a great deal more. In tests made in Nuremberg, it has been found that smaller objects could be seen at a distance of about 2700 meters, larger objects at a distance of about 7600 meters, while with the same searchlight, under similar conditions in the Mediterranean, Egypt and Asia Minor, distances up to 12,300 meters have been obtained. Therefore, it is noticeable that a further problem arises, which might engage the efforts of the engineering profession, and that is to clear from the atmosphere suspended particles, mist and fog, and that would mark a very great step in advance in this problem. Possibly one of our confreres, Mr. Nicola Tesla, would be able to accomplish this, as it has something to do with the projection of energy through space; it is known that electrical energy of high tension will in some way clear the atmosphere.

H. A. Hornor: To the practical operating man, the searchlight must be more interesting on that side rather than on its theoretical side. The great improvement in the illuminating power of the searchlight is, of course, a very great advantage, not only from the standpoint of illumination, but also from the importance of its use.

I should like to ask Lieutenant McDowell to explain a little more clearly to us the operation of the lamp. As I understand it, the gas is formed by the use of alcohol, and I should like to know what the operation of the lamp is in that connection. It must be understood, of course, that this searchlight has its application upon a floating craft, whose electrical equipment has unusual care, but it is doubtful in my mind whether a searchlight of this particular type would be universally applicable. On a naval vessel of any size, such as a superdreadnaught, there would be sufficient intelligence of an electrical nature to take care of the operation of the lights. I doubt very much, however, whether on our ordinary passenger and merchant vessels the searchlight could be usefully operated. We have a rule in merchant practise that a searchlight must be at least 18 inches in diameter, to be useful on an ordinary merchant vessel, namely, a vessel of 300 or 500 feet in length. An important point is that the searchlight must operate with a minimum amount of attention, as you cannot carry a body of skilled electricians on merchant vessels, except those of large size, such as our transatlantic liners.

W. S. Franklin: If you have a mathematical point source of light at the focus of a true parabolic mirror, you get a parallel beam. If you have a larger source, you get a conical beam, and I think the speaker who preceded me is mistaken in thinking that there is a possible correction of the shape of a mirror which will eliminate the necessary divergence which comes from the employment of a large source of light.

I was very much interested in reading this paper by Lieutenant McDowell, and pleased to have him clarify his discussion of the luminous power of a searchlight. I would like to ask Lieutenant McDowell whether, in the actual use of the searchlight for picking up something which has not yet been located, it has ever been found advantageous to use what is called indirect or side vision, which sometimes shows objects so much better than direct vision in dim lights.

I wish to make one other point, not in connection with the paper, but in connection with a matter of terminology in photometry and illumination. The two kinds of vision to which I have referred are commonly called twilight vision and bright light vision, but it seems to me that the two types of vision would be designated better by the two terms block vision and detail vision. It is well known that if you are walking out on a very dark night, and a person approaches you, he will be very much more easily seen if he is at one side than if he is directly in front of you. This so-called twilight vision enables one to perceive only a block or blotch with no detail whatever and I think it should be called block vision. Vision by the central part of the retina, on the other hand. enables one to see details, it requires a much higher degree of illumination, and I think it should be called detail vision. These two words seem to me to be much more clearly descriptive than the words heretofore used.

The question I have asked Lieutenant McDowell is simply as to whether, in the use of the searchlight, any deliberate attempt has ever been made to use block vision instead of detail vision, in catching a first glimpse of the distant object to be located.

Clayton H. Sharp: One of the very good points about this paper is that it sums up in a comparatively few words a good deal of the theory of the searchlight, which theory is frequently misunderstood. As Professor Franklin has said, if we have a strictly mathematical point source at the focus of a true parabolic mirror, we would get a parallel beam of light, and the flux density of light down that beam would be uniform throughout, except for atmospheric absorption. The diameter of the beam would be the diameter of the mirror. When the size of the crater becomes appreciable, the angle made at the surface of the mirror by the crater, which is called by Lieutenant McDowell the angle of dispersion, sometimes called the angle of divergence, determines the divergence of the beam as it leaves the mirror. So by increasing the size of the crater the size of the beam at a distance is increased, but the maximum flux density in the beam remains the same.

The point in regard to the Beck lamp is that it produces a luminous area having a higher average brightness than does the ordinary lamp. It has been pretty generally conceded that in the carbon arc the brightness of the brightest part of the crater is practically independent of the current density. If the current density is increased, the area which has the maximum temperature is also increased, but the brightness of the maximum part is not increased to any great extent. This brightness represents, in other words, a temperature corresponding to the vaporization point of the carbon. In the Beck lamp the end of a small carbon is solidly covered with an intense white light, giving a useful area of higher average brightness than the ordinary carbon; consequently the beam is homogeneous and the useful output of the searchlight is increased.

There is a characteristic difference between Fig. 10 of the paper, which shows the Beck light curve, and Fig. 11, which shows the distance curve of the navy standard 60-in. The Beck lamp gives an extreme point distribution which corresponds to a small crater. The navy standard gives one which is much less pointed, and where the point is much lower. That corresponds to the lower average temperature of the useful area.

I fail to see why having a larger crater is in itself a disadvantage. If you can only heat up the larger area to the same temperature you will get a larger beam, which I should think must be an advantage, and also as high a beam candle power as in the other case.

There are one or two statements in the paper which I think require some explanation. "The sides of this crater reflect the light radiation to the focus of this crater, and in addition the light from the negative is reflected, so it is believed nearly true black body radiation is obtained." The statement is made below that the incandescent gas in the crater shows bright lines, consequently its temperature must be higher than the temperature of the carbon, and on the next page it is stated that the temperature of the incandescent gas within the positive crater is estimated to be between 5000 and 5500 deg. cent. It seems to me that there are some inconsistencies there. If there is a true black body, it cannot reflect and it cannot contain a gas at a higher temperature. If the temperature of the gas is only the temperature of the carbon surface, then the bright lines must be due to luminescence of the gas; in other words, the gas gives outlines corresponding to a higher temperature than the black body temperature. That does not necessarily mean that the gas itself has that higher temperature. I should like very much to know how the estimate of 5000 to 5500 deg. cent., as the temperature of the gas, is made. I should also like to know the basis of the estimate that the aggregate quantity of blue and violet rays in the Beck lamp is about 23 per cent. The unit of measure there, or the terms on which that is expressed, would help to an understanding of the statement.

Karl Georg Frank: I hope there is no need here for my standing up for the theory of ionization, and while there may be different opinions about it, I want to point out the following fact. In speaking of the evaporation of carbon, one naturally thinks that, like all other bodies, the carbon first becomes liquid and then evaporates. Not only Lummer, but also Braun made tests and Lummer thinks even today he has been able to liquefy carbon at about 5000 or 6000 deg. cent., but he is not sure, and other people are not sure, either. Other experiments have been made to discover at what temperature carbon would evaporate; the experimenters used temperatures up to 3000 deg. cent., but they could not exactly determine what happened.

One of the speakers pointed out that the carbon is consumed at a lower rate, but that is decidedly not evaporation, but oxidation. In steel making it is known that oftentimes, at as low as 1000, 1200 or 1500 deg. cent., carbon is readily oxidized into the form of CO, and we have to deal with similar cases in the arc of the ordinary arc lamp. What I pointed out was that evaporation, that is to say, throwing out of carbon particles, without oxidation, probably does not take place at such a low temperature as 1800 deg. cent. without the formation of an arc. We have a similar, and yet in some ways an entirely different phenomenon occurring in the incandescent lamp where we have a carbon filament; a deposit of carbon on the glass is noticed, due to the vacuum to some extent, and also, very probably, ionization takes place. I believe in most similar cases where we have to deal with a consumption of carbon at a temperature of between 1000 and 2000 deg. cent., it is not, strictly speaking, evaporation, but oxidation, a formation of gaseous solution, with a possible consumption of carbon itself.

Introductory address delivered at the 3rd Mid-winter Convention of the American Institute of Electrical Engineers, New York, February 19, 1915.

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ELECTRICAL PRECIPITATION

Historical Sketch

BY F. G. COTTRELL

MY FUNCTION this morning is merely to present a brief introduction to the real speakers and their topics. What you are chiefly interested in at this time, I know, is the experimental side of this matter, including the lantern slides and motion pictures, which these speakers have to show you. All I shall try to do is to outline a few of the steps that have led up to this work and thus attempt to give it a little more definite setting in time and space.

Going back to the earliest reference on the application of electrical forces to precipitation, we find that M. Hohlfeld, in 1824, was the first, as far as I know, to point definitely to the phenomena as of practical significance. Hohlfeld was a teacher of mathematics in the Thomas School of Leipzig, and published a brief article[1] descriptive of an experiment he had made on this subject. What he did was simply to form a funnel out of a piece of paper, set the lower tip into a bottle, and light the edge of the paper. When the smoke filled the bottle, the stopper was inserted with a wire through it reaching to within about three inches of the bottom. This wire was then connected to an old-fashioned frictional electric machine, and upon operating the latter the smoke in the bottle quickly disappeared by deposition on the inner surface. One of the experiments which Mr. Bradley is to show you later is substantially a duplicate of this experiment of Hohlfeld's. It is perhaps worth while to note the words in which Hohlfeld expressed his ideas on the significance of this phenomenon. He writes:

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[1] Kastner's *Archiv für die Gesammte Naturlehre,* Nürnberg, 2, 205-206 (1824).

"It is, of course, well known that during a thunder-storm, after almost every bolt of lightning, there comes a heavier fall of rain, and this occurs, indeed, just such a period after the bolt as would be required for the water to reach the earth from the clouds. It has also been observed that following a thunderclap, and especially the heavier ones, sleet and hail often fall and in increasing amounts with repetition of the discharges. Finally, it has been noted that so-called cloudbursts are usually preceded by strong and rapidly repeated discharges. The first of these phenomena may easily be illustrated with the use of artificial electricity."

Then he describes the experiment of which I have spoken. This constitutes our first historical reference to this subject, so far as I know.

This fell, apparently, on deaf ears, no one appreciating its importance. The machinery at the time available was, of course, inadequate for commercial application, and nothing again appears until a quarter of a century later, when C. F. Guitard mentioned[2] a similar phenomenon, which he independently observed on tobacco smoke in a bottle in much the same way. Then, the matter seems to have again rested for a still longer interval without further notice, save for an occasional incidental reference. For example, in 1878 Robert Norwald cites[3] the dispersing of dust inside an electrometer he was working on, when the instrument was left charged, which he ascribed to this cleaning effect on the air. The reference, however, is merely incidental, and represents nothing that was put to practical use.

The first attempt actually to apply this principle to practical affairs seems to have come almost simultaneously in Germany and in England. We find under date of August 9, 1884, an English patent on electrical precipitation issued to A. O. Walker, one of the proprietors of a large English lead works, and also a German patent, dated October 2, 1884, issued to Dr. Karl Moeller, covering much the same general ideas. Both of these seem to be entirely independent of the earlier work, and to represent, practically, rediscoveries of the phenomena of electrical precipitation. Walker's patent was directly inspired[4] by experiments and observations made by Prof. Oliver Lodge and presented by him about that time in several lectures.[5]

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[2] *Mechanics Magazine*, London, Nov. 1850.

[3] *Wied. Ann.*, *5*, 460-499.

[4] "A New Application of Electricity," editorial in *Engineering*, London, *39*, 627-628; June 5, 1885.

It is interesting to note in these papers presented by Lodge, that the phenomenon which he was primarily studying was not electrical precipitation at all, but that this only came up as an accident of an independent investigation, he having set out originally to study the effect of hot and cold bodies on dusty air. It had been known for a long time that if a hot iron rod were held in a cloud of smoke or dust and one looked along the edge of the rod he could see a dark space between the rod and the surrounding cloud of smoke or dust, and already considerable work had been done by various investigators to explain this phenomenon. It was at first assumed to be due to the combustion of the particles surrounding the rod. This was later disproved and the effect finally was run down to a question of molecular bombardment. Lodge, in attempting to determine whether any electrical forces were associated with this purely thermal phenomenon, tried the effect of electrifying the heated rod. Up to potentials of a hundred volts or so he found no appreciable effect, but on going to thousands of volts he was surprised to find that a manifest activity was produced, that the smoke or dust was driven away from the rod, and rapidly deposited. It was only later that he came across references to the observations of others, and published a brief historical note[6] citing them and giving credit to these early investigators for their work, which was unknown to him at the time of his own discoveries.

These lectures and papers by Lodge served to bring the subject clearly before the public, and I think it is fair to say that the place of precipitation in our modern thought dates from that time. The work of Moeller, while following somewhat the same line, does not seem to have produced the same effect on the public, probably because it only appeared at that time as a patent, and was not followed by any further general publicity, and thus largely escaped public attention.

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[5] Lodge preliminary letter, *Nature*, *28*, 297; July 26, 1883.

Lodge and Clark, *Proc. Roy. Soc.*, Feb. 1884.

Nature, Apr. 24, 1884. Lecture by Lodge before Roy. Dublin Soc.

Nature, Jan. 22, 1885. Lecture by Lodge before Brit. Ass'n. Advc. Sci., Montreal Meeting.

Proc. Roy. Institution of Gr. Br., *11*, 520-529. Lecture by Lodge before Roy. Inst. May 28, 1886.

Jour. Soc. Chem. Ind., *5*, 572-576 (1886). Lecture by Lodge before Liverpool Section of Soc. Chem. Ind., Nov. 3, 1886.

[6] *Nature*, *71*, 582 (1905).

While we find Lodge's work referred to in various journals from that time down to comparatively recent years, and a number of patents covering details of proposed methods occurring here and there in the literature, there was nothing that could fairly be considered as a permanent contribution to the actual industrial development of the subject until quite recently.

Just following Walker's original patent, an installation was made[7] at his plant, the Dee Bank Lead Works in England, in which two large Wimshurst influence machines were relied upon to supply the electricity. The Wimshurst machine had just come out at that time, and the descriptions of this plant are especially interesting today on account of the terms in which they describe the Wimshurst machine. It was so vastly superior to the friction machines in use before that time that it was considered a commercial piece of apparatus, a thing which would revolutionize the industry, and bring static electricity into practical use, which we know has not been the case in any such measure as was anticipated.

Current from these two large Wimshurst machines, whose rotating disks were five ft. (1.5 m.) in diameter and were driven by a small steam engine, was carried to the flues of the lead works and there discharged into the gases from an insulated system of rods studded with sharp points placed in the flues, the other terminal of the machine being grounded. The installation, however, proved impracticable to maintain in commercial operation and was eventually abandoned.[8]

About 1905 some of us happened to be interested in these same problems, more specifically the clearing of fumes from certain acid works in California, and experiments were undertaken at the University of California to determine the practicability of these general methods, using more modern apparatus, and substituting the high-tension transformer with the auxiliary apparatus necessary, for the influence machine, and working out a more efficient system of electrode distribution.

Out of that grew some interesting laboratory experiments which looked promising, and these attracted the attention of the local manufacturing concerns who were willing to carry the work further. It was very soon found that the work would have to be put on a more stable basis than it was possible for us to do as we were then working.

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[7] W. M. Hutchings, *Berg- und Huttenmännische Zeitung*, *44*, 253-254 (1885).

[8] "The Condensation of Fume by Static Electricity," Malvern M. Iles. *School of Mines Quarterly*, N. Y., Vol. *16*, No. 4, July 1895; and Vol. *17*, No. 2, Jan. 1896.

This was what led, eventually, to the organization of the Research Corporation. It was realized that it would be difficult for the University itself to undertake this work, and there was a distinct prejudice against permanently commercializing the matter in the hands of any one private industrial organization. A plan was therefore worked out to develop the patents under the guidance and backing of local capital, with the understanding that when the money invested had been returned, and a reasonable profit secured, then the patents as a whole, or at least a large portion of them, should go over to some holding organization to be used for the benefit of scientific research. It was expected then that the University of California would probably become the recipient, because all of us who were working on the problem at that time were alumni of that institution. As the work developed it took more time and money than was anticipated, and by the time it had become stabilized, which was a matter of five years, the work had spread over such a large territory that it seemed inexpedient to attempt to administer it from a single local institution. We also foresaw the danger, if it became successful and was handled from one such institution, that the same sort of procedure would naturally be emulated elsewhere, and before one knew it the very thing which we wished above everything to prevent, that is, the commercializing of educational laboratories, would be really brought about by the fact that they would be competing among themselves on a commercial basis, the most dangerous effect that could be brought about. To obviate this, we looked for a solution in finding some national, and better, international, body, to undertake the administration of these rights, and any others that might come in the same way—an organization with and through which all the different academic activities, universities and colleges could cooperate.

To make a long story short, after considerable search for the best means of carrying this out, the patents were offered to the Smithsonian Institution, and by it transferred to a Board of Trustees which was formed under its auspices and guidance, and called the Research Corporation.[9] This was organized as a business corporation with directors and a charter, to conduct the commercial development of the patents, and to turn over the profits to the Smithsonian Institution to be used at the latter's discretion in aiding and encouraging scientific investigation throughout the institutions of learning of the world, for which it acts as a sort of clearing house, and it is under the guidance of the Research Corporation, with which probably many of you are already familiar, that the work which grew out of the activities in California has developed.

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[9] *Jour. Ind. and Eng. Chem.*, *4*, 864-867, Dec. 1912.

Right alongside of the latter came also a somewhat similar development here in the East. About the time we were starting out on the final consolidation of this work under the Smithsonian and the Research Corporation, Professor Robert Kennedy Duncan was crystalizing his work on industrial fellowships at the University of Pittsburgh.[10] I presume most of you are familiar with the system of industrial fellowships at the Universities of Kansas and Pittsburgh. One of the problems which Prof. Duncan undertook as a part of this general program in Pittsburgh was that of smoke and dust elimination. We worked in the West particularly on smelter smoke, and in the East he and his co-workers concentrated their efforts more on coal smoke, their more specific field being the city of Pittsburgh.

Out of this, together with the work on other fellowships which was in Prof. Duncan's hands at that time, finally grew the Mellon Institute of Industrial Research and School of Specific Industries, located in Pittsburgh, and the beautiful new building, which is to be dedicated this coming week, stands as a splendid and fitting monument to Dr. Duncan's energy and devotion to that work. He was, most lamentably, taken from us last year by death, just at the time when his long-cherished dreams were blossoming into substantial realities, but, as he told me shortly before his death, he felt that the work had then come to such a point that it would stand. He fully realized the uncertainty of human life and said he had until lately been apprehensive for fear he might not be able to carry the work far enough to have it thoroughly stabilized before he should be taken, but that it had been carried to such a point in the last few months that that fear was eliminated, and at last it had reached a stage and was in hands which left his mind at ease, referring particularly to his associate, Dr. Raymond F. Bacon, who has since succeeded him as director of the Institute.

The original program of the Mellon Institute in smoke abatement was wider than that of the Research Corporation. It covered not only electrical precipitation, but other fields, such as improved furnace construction and the like. Electrical precipitation played, however, a prominent part in it, and from the first, even before the details of his campaign were taken up, Dr. Duncan and I discussed the work and arranged a tentative plan of cooperation. At that time both the work of the Research Corporation and the work under his direction were still in such a formative state that it did not seem wise to try to make a formal arrangement between them, but rather to work it out as we went along, and it was decided we should follow this procedure until such time as the work on both sides was sufficiently developed to bring them into more definite interrelation.

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[10] *Jour. Ind. and Eng. Chem.*, *3*, 177-186, Mar. 1911.

That has since then in large measure been brought about, and the two institutions are now working together to a common patent situation—the patents developed by each are now, to a very considerable extent, being consolidated and utilized in a cooperative manner. The Mellon Institute and the Research Corporation are working for the same general aims, although their methods of administration and conduct of work vary somewhat, but they are mutually sympathetic and trying earnestly to extend to each other all the moral support possible. The field of the Mellon Institute in the precipitation work is expected to be more particularly in the vicinity of Pittsburgh, for the immediate future, at least, with the Research Corporation working cooperatively with them there, but also over the rest of the country, where work is already started.

These details will be understood better from the papers which are to follow. This morning Professor Nesbit and Dr. Strong will speak for the work of the Mellon Institute, and Mr. Bradley for that of the Research Corporation. It has been a great satisfaction to me to see this close cooperation come about, not only because of the greater practical efficiency for useful effort which it represents, but because I knew Dr. Duncan and valued his friendship very highly, and we both had this same view in mind, of thorough cooperation between the two organizations. I know there is nothing that would please him more than a knowledge of the results as they are now working out and the harmony of purpose and action between the two organizations, and I feel sure the same applies to Mr. Mellon, who has so generously endowed the work of the Institute. So much for the retrospect.

As regards the actual work, the speakers to follow and the apparatus will tell the story, so I will not attempt here to speak on that side of the subject, but I might perhaps say a few words in regard to our dreams of the future; in other words, as to the question—How far can this work go beyond what has actually been done and will be brought to your attention this morning in the papers? In Lodge's original plans there were two rather distinctly separate projects, two separate lines of attack. One was directed toward the precipitation or collection of industrial fumes and smoke—man-made fumes. The other was directed toward fog precipitation in the open, the clearing of routes for navigation, of congested railway terminals and crossings and even of metropolitan streets. It is natural to think of the famous fogs of London as probably a powerful stimulus to Lodge's imagination and interest in this matter. This, in one sense, looks like a greater task, a more hopeless undertaking, than those we have already to some extent accomplished. Still, it is a matter of such general public interest as to justify the most earnest effort in its attempted solution, and after all, there would seem to be nothing necessarily inherent in the engineering difficulties to be anticipated which would put it beyond the reach of present mechanical developments. It is a service which will probably require powerful apparatus, and the small installations that have served as stepping stones up to the present time have been a natural forerunner. Having developed the apparatus up to the point we have reached now, it is perhaps time to make a start, at least, on this new work.

Aside from these practical considerations, I must confess to having had a personal feeling of reticence in undertaking the fog problems proper, as I have always associated them particularly with Sir Oliver Lodge's own personality, and I had hoped that the work over here would eventually reach a sufficient basis in practical success so that by the time the real fog problems came to be taken up it might be possible to secure Sir Oliver's association directly with the work in such a way as would adequately indicate and recognize the credit that is due him as the father of this whole art. I had hoped that at last such an opportunity was about to present itself in the coming of the International Exposition at San Francisco, and particularly in the International Electrical Congress which was planned. Accordingly, efforts were made to arrange a program to carry out some of these experiments in their application to fog work at that time. These plans were well under way, when the outbreak of the war, as you know, made the holding of the International Electrical

Congress impracticable, and the matter then came back for consideration as to whether it was expedient to attempt anything at all. In the meantime, however, it was found that much of the apparatus desired had been pledged, and that there would probably be facilities for handling extremely high-tension, high-powered circuits at the exposition. The electrical departments of the two neighboring universities have taken an active interest in the matter and preparations are being made to do what can be done at the time of the exposition to carry on some, at least, of these experiments in general high-tension technique, and it may still be possible to get in a little work on the fog problems.

While here in the East on my present trip, it has been most pleasing to find the interest which is being taken in this matter. The possibilities of such experiments are growing right along among the shipping and other interests, to whom the fog question is a vital one, and I think it is entirely probable that within the next few months a direct start may be made in experiments along this line. Sir Oliver Lodge, it is understood, has carried out some very striking experiments in this direction already. On top of the Physics Laboratory in Liverpool, just before he left there to take his present post at Birmingham, he mounted an electrical conductor and charged it from a series of large electrostatic machines with the result, it is reported, that he was able gradually to dissipate the fog for a considerable distance around the conductor. This would seem, at least, to represent what may be hoped for where one has to do with quiet air and stationary objects. My own feeling is that the line of attack most directly connected with established practise in this country may probably lie in finding a means of carrying an electrode system, slightly modified from those now used in flue systems, out in front of the vessel to be protected from fog dangers. Aeronautical problems are coming fairly and distinctly into the field of the engineer, and in talking with aeronautic engineers I find they do not see why there should be any insuperable difficulty in carrying at a couple of boat lengths ahead of the vessel, from each side, an apparatus such as the electrode system, and connecting it to high-tension apparatus on shipboard through the cable that is supplying the helicopter's or dirigible's motor. You would thus have a broom, so to speak, sweeping a path clear in front of the vessel, that would give room enough to stop or turn aside as objects ahead were sighted. The light electrode system and its supporting mechanism can of course be deflected in a shorter time than that in which you can stop a large vessel. This picture is not put forward as a definite program or detailed project, but mentioned purely by way of suggestion as to one of the lines of work that may be taken up, and to indicate perhaps, to some, how it may not, after all, be as blind a jump into the dark as it would seem at first sight. Some of the steamship people in New York, and elsewhere, have expressed their willingness to go forward with the work should the preliminary tests prove encouraging, and it is hoped some such development may take place in the near future. In closing, I bespeak your cordial help and cooperation as members of the electrical profession in helping this work along, for it certainly should add very materially to the safety and comfort of people traveling at sea, as well as materially assist in solving many problems on land.

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ELECTRICAL PRECIPITATION

THEORY OF THE REMOVAL OF SUSPENDED MATTER FROM FLUIDS

BY W. W. STRONG

ABSTRACT OF PAPER

The frictional resistance of a small particle moving through a fluid is given by the law of Stokes. Knowing the density and size of the particles and the coefficient of viscosity of the medium, the amount of energy required to remove suspended matter from fluids can be calculated. From the formulas the relative efficiences of the different methods used to remove suspended matter from gases can be obtained. From these formulas the electrical method is shown to be especially adapted to fine suspended particles or to a mixture of gases that can be selectively ionized. In a practical case of electrical precipitation of smoke it is shown that approximately 4 per cent of the energy of the corona discharge is actually expended in the process of precipitation.

The manner of the distribution of the energy of the corona discharge is discussed. The nature of the corona ionization and the " corona " rays is also briefly described.

The application of the theory of electrical precipitation is given so that it is possible to determine the best working conditions for precipitating a given kind of suspended matter from a given fluid. The theory also indicates the limits of usefulness of the method of electrical precipitation

THE ENERGY REQUIRED TO REMOVE SUSPENDED MATTER FROM FLUIDS

IN GENERAL it may be said that the engineering problem of removing suspended smoke, fumes or dust from gases and liquids requires that these particles be given more or less velocity. The gases or liquid usually pass through the precipitation chamber with a certain velocity which we will designate as the *longitudinal* velocity. If the suspended matter can be given a *transverse* velocity independently of the velocity of the fluid, we have a way of separating the suspended particles from the fluid. Precipitation is therefore a process of subjecting smoke, fumes or smoke and gases to differential forces. Examples of the action of differential forces are given by " settling " due to the gravity forces, the centrifuge process (often applied in flues by the use of sudden changes in the direction of the flue gas current or in fans and centrifuge machines), the separation of suspended matter by the direct action of the electric and magnetic fields, or by the ionization methods as used in the Cottrell and corona methods of electrical precipitation.

In all these methods of precipitating smoke, fumes and dust the amount of energy actually required can be calculated by means of the law of Stokes provided one knows the size (radius of the suspended particles = a) of the particles, their density (d), their velocity (transverse velocity V_t), the number of particles (n) per unit volume of the medium and the coefficient of viscosity of the medium (μ).

As a typical example of the precipitation of fumes, smoke or dust let us assume that Fig. 1 represents a cross-section of the precipitation chamber. The length of the chamber is AB or L cm. and the distance between AB and CD is l cm. The longitudinal velocity of the gas through the chamber is V_l. In order that the fumes shall be precipitated it is necessary that they be given a velocity V_t such that they will all be carried to the walls during the time $\left(\frac{V_l}{L}\right)$ required for the gases to pass through the precipitation chamber. It will also be assumed that the particles stick to the walls, and this is partly accomplished through electrostatic attraction in the electrical method. Complete precipitation for the chamber represented by Fig. 1 therefore requires the transverse velocity (V_t) to carry the particles to either AB or CD. We may assume that in one half of the chamber the transverse velocity is towards AB while in the other half it is towards CD. (This can be approximated by having an electrically charged plate in the middle of the chamber and charging the smoke particles to an opposite sign).

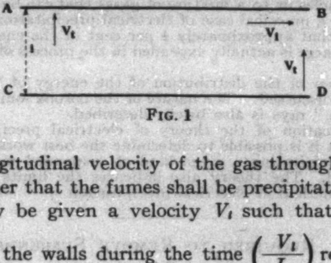

FIG. 1

We have, therefore, $\frac{1}{2}\, l/V_t = L/V_l$ (1)

Using a margin of safety of 1.2, we may say $\frac{1}{2} l V_l = 1.2 L V_t$ or

$$V_t = \frac{l V_l}{2.4 L} = 0.4 l V_l/L \tag{2}$$

Assuming our precipitation chamber to be one cm. thick, the volume of gas passing through the chamber per second is $l V_l$ cu. cm., and the number of particles passing per second is $n l V_l$.

Let E_p be the energy required to carry the particles through the gas with the velocity V_t and give them their kinetic energy which they eventually transfer to the walls of the chamber when they " stick " to it. Let F be the frictional resistance encountered by the particle and s the distance subjected to this frictional resistance. Then

$$E_p = \left\{ \frac{1}{2} m V_t^2 + F s \right\} n \text{ ergs per unit volume.} \tag{3}$$

For complete precipitation in the chamber of Fig. 1, and for the treatment of $l V_l$ cu. cm. of gas per sec.,

$$E_p \text{ in ergs per sec.} = n l V_l \left(\frac{1}{2} m V_t^2 + \frac{1}{2} F l \right) \tag{4}$$

The law of Stokes gives the value of the frictional force F and this law has been found to hold with a considerable degree of accuracy for wide variations in the radius, shape and nature of the particles. This law is:

$$F = 6\pi \mu a V_t d. \tag{5}$$

Equation (4) then becomes

$$E_p \text{ in ergs per sec.} = \frac{1}{2} l V_l (m V_t^2 + 6 \pi \mu a V_t dl) \tag{6}$$

or,

$$E_p \text{ in ergs per sec.} = \frac{0.2 l^3 d V_l^2}{L} \left(\frac{0.16 \pi a^3 V_l}{3 L} + 6 \pi \mu a \right) \tag{7}$$

In the case of smoke and most kinds of fumes and dust a is small, so that the term $\frac{0.16 \pi a^3 V_l}{3 L}$ is negligible. It is in this field that electrical precipitation is especially well adapted, since the forces acting on the smoke particles depend upon the number of ions striking the particle and on the charge of the particle. On the other hand, centrifuge forces vary as the mass of the particles and therefore as a^3. For centrifuging, equation (7) would remain as stated. For electrical precipitation (7) becomes

$$E_p \text{ in ergs per sec.} = \frac{1.2\,\pi\,\mu\,a\,l^3\,d V_l^2}{L} \qquad (8)$$

For practical purposes it is convenient to make the precipitation chamber as large as possible, but it is seen from equation (8) that this is impossible since l appears cubed. It is also seen that V_l cannot be increased very greatly even though the length of the precipitation chamber is increased. The greatest efficiency is to be attained, therefore, by making l and V_l as small as is practicable. In practical work, l should not exceed 5 or 6 inches, and V_l should not greatly exceed 8 or 10 feet per second. The maximum values of l and V_l are also limited by the nature of the corona discharge itself, as will be shown later.

THE CORONA DISCHARGE

The corona discharge consists of an electrical current carried by ions produced by the secondary ionization resulting from the impacts of rapidly moving ions with the gas molecules. For purposes of illustration and for practical electrical precipitation of smoke and fumes, the term corona discharge will be restricted to the use of an electrical discharge, taking place between a wire (placed axially) and its enclosing cylinder. The process of secondary ionization is accompanied by a number of transformations. Let E be the energy consumed in the discharge. Part of this energy is converted into the luminous effects of the discharge, (E_l), part in effecting chemical reactions, (E_c), in heating the electrodes, ($E_{h.e.}$), in heating the gaseous medium, ($E_{h.g.}$). We have, then,

$$E = E_p + E_l + E_c + E_{h.e.} + E_{h.g.} \qquad (9)$$

Several of these quantities ca nbe measured separately, so that it is to be hoped that our knowledge of these energy changes will soon be greatly extended

The nature of the ionization taking place during electrical discharges at low gas pressures has been studied by Thomson, Stark and others, and it will be assumed here that the kind and relative number of ions in the " corona rays " and the " corona streams of ions " is the same qualitatively as at low pressures. At atmospheric pressure, however, the ions will be shorter lived, less simple in constitution and will form less distinct rays, so that the phenomena will not be the same

The kinds of ions that may exist in oxygen and nitrogen for longer or shorter intervals of time are as follows: $\overset{-}{O}_2$, electrons, $\overset{-}{O}, \overset{+}{O}, \overset{++}{O}, \overset{+}{O}_3, \overset{+}{O}_6, -$, and charged nuclei. $\overset{+}{N}_2, -, \overset{+}{N}_1, -, \overset{++}{N}, \overset{+}{N}_3, -, \overset{+++}{N}_1$, and charged nuclei. Even at low gas pressures many of these ions appear very rarely, so that one may assume the corona ions to consist largely of $\overset{-}{O}_2, \overset{+}{N}_2, \overset{-}{O}, \overset{+}{N}, \overset{+}{O}$, possibly $\overset{++}{N}$ and some charged nuclei.

There may be several processes of ionization possible, the process at any place depending on the nature of the gas, the corona rays and the electric field existing there. With increasing field strength the order of appearance of these different types of ionization is probably somewhat as follows:

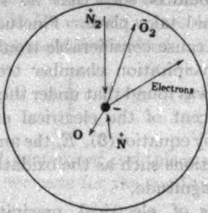

FIG. 2—NEGATIVE CORONA RAYS

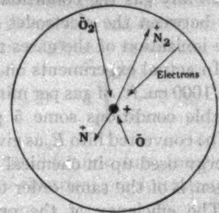

FIG. 3—POSITIVE CORONA RAYS

(*a*) Secondary ionization produced by the natural ions of the gas and by the electrons produced by this ionization. The ions are probably almost entirely of the $\overset{-}{O}_2$, and $\overset{+}{N}_2$ type. As the potential gradient (depending on whether there is a + or − corona) is increased, (*b*), ions like $\overset{-}{O}$ and $\overset{+}{N}$ are formed. The different ions probably begin to ionize by collision for different potential gradients, so that the nature of a corona ray depends on the value of this gradient.

The nature of the corona rays is not well known but they are probably somewhat like those represented in Figs. 2 and 3, the positive and negative corona rays being quite different. At low pressures there would be many more electrons, $\overset{+}{N}_2$ and $\overset{-}{O}_2$ rays, than of the other types. The positive brushes may consist of regions where ions recombine. These brushes are very ineffective as regards precipitation, fumes and smoke being almost entirely unaffected by them. It seems necessary for precipitation that the suspended particles be subjected directly to the corona rays that are themselves producing secondary ionization. This would lead one to the view that precipitation is not the immediate effect of the electric field on the charge of a smoke particle but that it includes the kinetic energy received by the particle due to collisions with the corona rays.

BEST WORKING CONDITIONS FOR ELECTRICAL PRECIPITATION

1. The best working conditions for electrical precipitation seem to include the action of as uniform and dense a corona as possible upon the gas containing the suspended matter.

2. The effect of temperature is not very great, higher temperatures usually permitting of a larger corona current density.

3. In any gas the conditions should be such that no breakdown between the electrodes should take place. Fluctuations in the ionization of the gases may cause considerable trouble.

4. In actual experiments on a precipitation chamber treating about 1000 cu. ft. of gas per min. it was found that under the most favorable conditions some 5 per cent of the electrical energy could be converted into E_p as given by equation (**8**). E_c, the amount of energy used up in chemical reactions such as the oxidation of nitrogen, is of the same order of magnitude.

5. The efficiency of the process of electrical precipitation is probably not as great as represented by (**8**), since the corona discharge is not distributed altogether uniformly over the wire.

6. The theory of electrical precipitation can easily be applied to that of a corona wire fixed axially in a cylinder of radius R. Consider a cylindrical shell of the thickness dr at a distance r from the center of the cylinder.

The energy required to remove the particles in this shell (volume $= 2\pi\, r\, dr\, L$) of number $2\pi\, r\, n\, L\, dr$ would be equal to the kinetic energy the particles impart to the cylinder on impact and the energy used up in frictional resistance. One has

$$E_p \text{ for this shell per sec.} = \left(\tfrac{1}{2}\, m\, V_r^2 + (R - r)\, 6\, \pi\, \mu\, a\, d\, V_r\right) 2\, \pi\, r\, n\, L\, dr,$$

$(R - r)$ being the distance that each particle must traverse in order to reach the outer cylinder. For the whole cylinder this becomes

$$E_p = \int_{r=b}^{r=R} \tfrac{1}{2}\, m\, V_r^2\, dr + 12\, \pi^2\, r\, n\, L\, (R - r)\, \mu\, a\, d\, V_r\, dr \qquad (10)$$

in which b is the radius of the wire electrode. Since the particles have reached a state of equilibrium in each shell (the forces of the electric field and the frictional forces being balanced) V_r is a function of the potential gradient, this latter being a function of r; r then is the only variable in (**10**), so that the expression can be integrated. In this way tables connecting E_p with the amount of corona current, the changes in the gas viscosity, temperature, the potential gradient, etc., can easily be determined.

The best method of attacking equation (**10**) from an experimental point of view is to work with smoke particles of uniform size and density (lycopodium dust, for instance), and measure V_r, m, μ, d and n. As the law of Stokes has been proved to hold experimentally for wide ranges in the value of a its use permits us to determine the electrical forces that are in more or less equilibrium with the viscous force of resistance. A determination of V_r for various values of r will serve to indicate how the smoke particles are ionized. Equation (**10**) may be written:

$$E_p = A\int_{r=b}^{r=R} V_r^2\,dr + B\int_{r=b}^{r=R} r\,V_r\,dr - C\int_{r=b}^{r=R} r^2\,V_r\,dr.$$

Since A contains a^3 and this is very small for fine dust, fumes and smoke, we have for the conditions of electrical precipitation:

$$E_p = B\int_{r=b}^{r=R} r\,V_r\,dr - C\int_{r=b}^{r=R} r^2\,V_r\,dr. \tag{11}$$

The transverse velocity of the ionized smoke particles (V_r) is a function of the potential gradient (E_r) at r and in the direction of r.

$$V_r = f\,(E_r) = f\left(\frac{E}{r\log\frac{R}{b}}\right) \tag{12}$$

It is thus seen that since E is not a function of r, being the difference of potential between the wire and the cylinder, (**11**) can be integrated. The value of the function f is determined by the size and manner of charging the smoke particles by the corona rays. This is not now well known. We have then for the energy consumed,

$$E_p = B\int_{r=b}^{r=R} r\,dr\,f\left(\frac{E}{r\log\frac{R}{b}}\right) - C\int_{r=b}^{r=R} r^2 d\,r\,f\left(\frac{E}{r\log\frac{R}{b}}\right) \tag{13}$$

For an example, cigarette smoke was taken. Very dense cigarette smoke may contain a maximum number (n) of 30,000,000 particles per cu. cm. In the actual experimental conditions V_r was assumed uniform and was about 20 cm. per sec. $L = 4$ ft. a was assumed to be 0.01 μ (ranges between 0.1 to 0.001 μ, μ being a thousandth of a mm.), and the coefficient of viscosity 0.000178. The particles were all assumed to traverse a distance of 8 cm. The value of E_p then comes out to be some 20 to 30 watts (per thousand cu. ft. of smoke) and the corona energy consumption 300 watts. This value of E_p is only intended to be a qualitative illustration, but under actual conditions it can be determined with a considerable degree of accuracy.

CONCLUSIONS

1. It is shown that the energy (E_p) required for precipitating smoke, fumes and dust can be represented by the formula

$$E_p = K\, V_l^2\, l^3$$

where l is the length of the precipitation chamber, V_l is the necessary longitudinal velocity of the particles and K is a constant that can easily be determined in practise.

2. A formula is derived for the corona method of electrical precipitation that will give the efficiency of the process for pipes of different radii, different lengths and for different values of the potential gradient and the transverse velocity. For installing a plant the problem consists in knowing the constants of this formula and then deriving the most suitable type of precipitation chamber.

3. The possible nature of the corona rays is described, the different kinds of ionization that may take place and the way smoke and fume particles may be charged.

4. The distribution of the energy transformations in the corona discharge is outlined and it is shown how it is possible to measure some of these energy terms.

5. It has been shown that approximately 10 per cent of the energy of the corona discharge may be used directly in precipitating smoke. There is no doubt but that this efficiency may be increased.

6. It can be shown that a similar percentage of the energy may be used in the oxidation of the nitrogen by the corona discharge.

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THE THEORETICAL AND EXPERIMENTAL CONSIDERATION OF ELECTRICAL PRECIPITATION

BY A. F. NESBIT

ABSTRACT OF PAPER

Theory of electrical precipitation of suspended matter in gases is inseparably connected with the phenomena of ionization and the laws of electrically charged bodies.

The motion of the suspended particle is like that of the charged pith ball in the familiar experiments, but the charge is obtained by ionization instead of contact.

The paper shows that electrical precipitation occurs in nature and then by calling attention to the structure of matter shows how ionization is brought about, how the ions, nuclei and aggregates are formed, and the final precipitation of these is effected by gravitation and the electric field.

Experimental apparatus for electrical precipitation is given and attention is called to the differences between the appearance of the positive, negative and alternating corona.

The experimental data have shown the superiority of the negative corona and the relative effectiveness of the size and shape of electrodes, temperature and conductance of gases, polarity and uniformity of corona.

INTRODUCTION

THE theory of electrical precipitation of suspended matter in gases and liquids is inseparably connected with the phenomena of ionization, and the laws of electrically charged bodies. In order then that we may become familiar with the facts that underlie electrical precipitation, it has been thought best to give a somewhat detailed outline of the present theories of ionization, followed by the results of experiments made to study the phenomena.

Everyone is familiar with the experiment in which a pith ball is brought up near a body negatively charged. The near and far sides of the pith ball accumulate positive and negative charges of equal magnitude respectively. This polarization or separation of the electric charges, constituting the neutral state of the pith ball, into the respective components, and the greater or less freedom with which either of these components may become detached from their holder, the pith ball, and become attached to, or else remain free from other material molecules, represent phenomena which occur in splitting up the molecule or group of molecules in its neutral state into its electronic and ionic components respectively. This analogy is helpful in getting a correct view of the migration of charged bodies in an electric field; but the cause of the charge, the structure of matter, ionic migrations, and ionization agents must be considered at the outset.

As shown later, the particles suspended in a gaseous medium or constituting the solid and liquid particles of a moving gaseous stream, whenever they are subjected to the action of intense electric fields, become charged by the action of the traveling ions and electrons and consequently tend to travel along with these ionic streams.

1. The General Properties of Particles Suspended in Gases

Light reflected from very fine particles held in suspension in a gaseous medium is usually of a bluish color, and this color is purer the smaller the particles. As the particles increase in size, the reflected light becomes a pale blue and finally white when all wave lengths are equally well reflected. This phenomenon is observed on an enormous scale in connection with the blue sky, the brilliant sunsets, electrical discharges during thunder storms, and during the occurrence of the Northern lights, and shows the presence of suspended particles. The presence of atmospheric dust and moisture, along with the electrical phenomena which are taking place in the earth's atmosphere, is largely responsible for the precipitation of the so-called floating particles in the air. This is electrical precipitation occurring on an immense scale in nature.

The problem to which our attention is here called, is that which undoubtedly accounts in a large measure for the meteorological phenomena of the condensation of suspended water particles into rain, the formation of fogs and mists, the formation of snow, the presence of ice crystals at high air elevations, and the electrical phenomena occurring at these same high altitudes. The combined effects of these natural phenomena, with the presence of floating particles of man's own making, have an important bearing on climates, vegetable and animal life.

2. The Atomic Structure of Matter

The modern theory of matter is that it is composed of atoms, each one of which is of the same size. Likewise, charges of electricity are composed of the so-called electrical atoms, each of which is made up of the same quantity of electricity. The molecules of all material substances, whether gases or fluids, when in their neutral state, are said to possess equal quantities of positive and negative electricities.

Recent investigations and deductions furnish evidence which leads to the view that at least a part of the mass of an atom of any element is of electrical origin, and that the atoms of different elements differ only in the number and grouping of the ultimate units of negative charge called electrons. The electron represents an amount of negative electricity equal to 4.8×10^{-10} electrostatic units. No accepted name has been given to the ultimate unit of positive electricity corresponding to the electron, because no exact information is available as to the way in which positive electricity exists in the atom.

When an electron has been added to a particle or molecule of any substance, in the neutral state, it is then said to possess a free negative charge of 4.8×10^{-10} electrostatic units. When an electron has been removed from a particle or molecule, in the neutral state, it is then said to have a positive charge of 4.8×10^{-10} electrostatic units.

3. IONS, NUCLEI, AGGREGATES

Experiments on the electrical conductivity of gases suggest that this property of gases is greatly increased by raising their temperatures. This fact, coupled with the statements made above, leads to the conclusion that the molecules or particles of the gases themselves, apart from any suspended solid or liquid matter which they may contain, become better conveyers of electricity as their temperatures are raised. These charged particles or molecules of the conducting gas, or the suspended particles of vapors, dust, fumes, etc., which it may hold in suspension, are called ionized particles, and some are charged positively, others negatively, the two kinds of charges not necessarily being of equal magnitude.

A negative ion, or a carrier of a negative charge, is formed when a neutral molecule of a material substance, such as a particle of dust, vapor, or smoke, has imparted to it from any source whatever one or more electrons in excess of the number contained in its neutral state. The magnitude of the charge on the negative ion depends upon the number of electrons which have been added to the neutral molecule, or aggregate. In like manner, a positive ion is formed when a neutral molecule or aggregate of a material substance has one or more electrons removed from it.

These ions themselves may become the centers or nuclei about which large aggregates of the particles of the body may be clustered or assembled, and their charges may in part neutralize each other, or give rise to increased potentials for the aggregates above that of the individual ions.

An illustration of this principle on an enormous scale is the usual consideration of the myriads of minute water particles floating in the air. The clouds are great masses of water vapor, dust particles, and other floating matter in the air. This floating matter may exist more or less in the form of aggregates. The aggregates may have been formed by the condensation of water vapor on the dust or other particles as nuclei, or during their fall due to gravitation they may unite to form small drops. The drops of water are more or less charged with positive electricity, probably due to evaporation taking place at the surface of the earth and upon bodies of water.

When condensation centers begin to form, the aggregates have a resultant charge equal to that of the individual particles composing it. Thus, when an aggregate of eight water particles is formed into a sphere of twice the radius of the individual particles, that is, into a sphere of twice the electrostatic capacity, the potential of the aggregate is raised to four times that of the original particles.

4. IONIZATION

By ionization is meant that process by means of which the molecules of matter are split into positively and negatively charged particles or positively charged particles (ions) and electrons. The principal ionizing agents are Roentgen and Becquerel rays, cathode and other rays, the electric field, high temperatures, ultra-violet light and chemical action.

The phenomena of ionization are considered under the four following heads:

a. *The Action of High Temperatures*. When the temperature of a body becomes sufficiently high, the velocity of some of the electrons is so great that their excursions carry them beyond the surface of the body and they escape into the surrounding medium. Simultaneously with the escaping of the electrons from the hot or incandescent body, there may be emitted particles or molecules of the body itself, and these particles with their associated negative and positive charges constitute the streams of negative and positive ions.

b. *Thermions. Thermionic Currents.* In the case of hot or incandescent bodies, the ions which are emitted are called thermions. The density of these ionic streams constitutes what is called the density of the thermionic currents, and depends upon the physical and chemical conditions of the hot body at the time, its temperature, and the properties of the medium into which the ions are emitted or radiated. This thermal ionization from the fuel and the hot surfaces in the furnace or fire box may aid somewhat in giving an initial charge to the particles with which we are concerned in the electrical precipitation of smoke.

c. *Chemical action* may be the cause, as well as the result, of ionization.

d. *Ionizing Action of Water Sprays.* Wilson[1], Eve[2], Pomeroy[3], and others have investigated the ionizing action of fine jets of water in the form of sprays, and the conclusion is reached that both negative and positive ions are produced, the former being slightly greater in number than the latter. It may be possible that the ionization produced by water jets may have some valuable effect in the removal of suspended matter in air washers. The positively charged ions are associated with the heavier parts of the spray. The electrons, however, seem to attach themselves with great difficulty to water drops even though they be of very small sizes. These facts may explain the positive electrification of atmospheric clouds as due to evaporation of water.

Armstrong[4] studied the electrification of steam jets, and one of the conclusions he reached is that the electrification developed did not appear to depend upon the degree of violence with which the steam came into contact with the air. The work of Armstrong may shed some light on our subject.

THE THEORY OF ELECTRICAL PRECIPITATION

In general, solid and liquid particles may be considered as susceptible to the action of either or both the electric and magnetic fields. Only a few kinds of particles are acted upon by the magnetic field, and the most important application of the magnetic field is in the separation of iron ore dust from the earthy subtances with which it occurs in nature. We must keep in mind that every electromagnetic field is made up of its two inseparable components, the magnetic and electric fields respectively. Since the action of the magnetic field depends upon the more or less polarization of the particles to be removed, and is accounted for in a manner similar to that which explains the phenomena associated with the electric field, it will not be discussed in this paper.

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[1] *Philosophical Magazine,* July 1902.

[2] *Philosophical Magazine,* p. 382, 1907.

[3] *Physical Review,* 27, p. 492, 1908.

[4] *Philosophical Magazine,* Vol. 17, 1840.

Material particles, for our purpose, may be grouped in two classes, conducting and non-conducting. When the conducting particles are brought into an electric field, they immediately take up a definite redistribution of their charges which constitute their neutral state; each side of the particle has an accumulation of positive and negative electricity respectively, and it is customary to represent this condition by saying that the electric field has polarized the particles. Independent of this polarizing action, there may be either or both positive and negative ions, and electrons, present in the field, and these ions and electrons as a result of collisions among themselves and with the polarized particles will tend to combine with the latter and form what are called large ions or aggregates. Ions of this type are continually yielding up or receiving charges, and in a medium in which the density of the suspended particles is very great and the particles of minute size, it is quite probable that the formation of aggregates is hastened by the polarizing action. The velocity of the large ions is very low, and such being the case, special consideration must be given to these facts in the design of a precipitator to treat such particle-laden gaseous streams.

It may be inferred from what has previously been said, that the greater number of possible applications of electrical precipitation is concerned with the treatment of gaseous streams laden with solid and liquid particles of the non-conducting type.

Research Work on Electrical Precipitation

Some idea of the phenomena attending the precipitation of suspended particles in gases by the electrical process was obtained by means of special apparatus as shown by Figs. 1, 2, 3, and 4. The glass cylinder, Figs. 1 and 4, six in. inside diameter, completely enclosing the quarter-inch wire-mesh cylinder five in. in diameter, was sealed to the lower glass jar and also to the upper glass jar or pipe leading to the suction fan. There was thus eliminated any possibility of an in-draft of air through the wire mesh cylinder which constituted the grounded electrode.

The wire *c* in Figs. 1 to 4 represents the active electrode of the system, and was placed axially within the wire-mesh cylinder, being supported at either end by means of heavy-walled glass tubes *dd*. Connection to the high-voltage electrical circuit was made through the upper glass tube *d*.

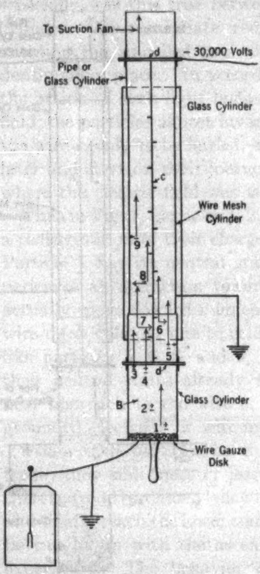

To Suction Fan
d
- 30,000 Volts
Pipe or Glass Cylinder
Glass Cylinder
c
Wire Mesh Cylinder
9
8
7
6
5
3
4
d'
B
2
1
Glass Cylinder
Wire Gauze Disk

FIG. 1

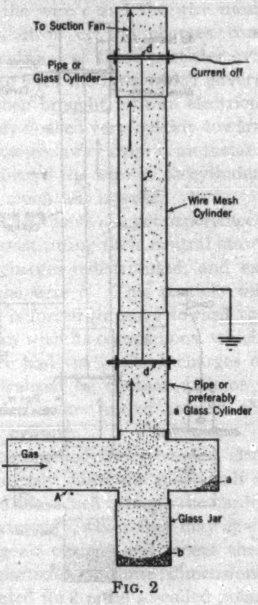

To Suction Fan
d
Pipe or Glass Cylinder
Current off
c
Wire Mesh Cylinder
d'
Pipe or preferably a Glass Cylinder
Gas
a
A
Glass Jar
b

FIG. 2

In the experiments to be described, all cylindrical parts of the apparatus were of glass, except the wire-mesh cylinder and the cross *A* of stovepipe in Fig. 2. Ample insulation was thus provided against any leakage of electricity from the active electrode *c* to any part of the apparatus, except corona discharge between the wire *c* and the grounded wire-mesh cylinder.

The electrical circuit consisted of a high-voltage transformer capable of stepping up from 220 volts to as high as 80,000. The high-voltage side of this transformer was connected through a mechanical rectifier of the Lempe type, and one side of the circuit was taken to the upper end of the active electrode *c*, the other side going to ground. A potential of about 30,000 volts was needed to get a strong negative corona discharge from the wire *c* toward the wire gauze.

Referring now to Fig. 1, very fine pieces of thin tissue paper, tin foil and gold leaf, fine shreds of silk fiber and other light substances were placed on the wire gauze disk. Every precaution was taken to insure that these particles of paper, etc., were free from any electrical charges, the disk being first connected to a delicate gold leaf electroscope, which gave no indication of charges, and then grounded.

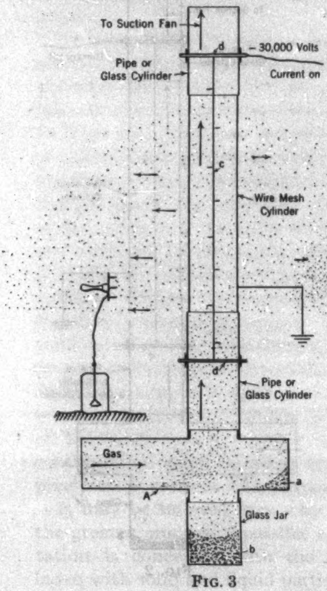

To Suction Fan
d
– 30,000 Volts
Pipe or Glass Cylinder
Current on
c
Wire Mesh Cylinder
d
Pipe or Glass Cylinder
Gas
a
A
Glass Jar
b

FIG. 3

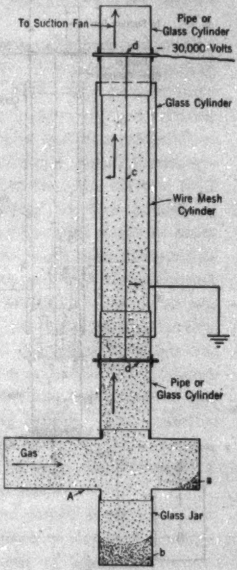

To Suction Fan
Pipe or Glass Cylinder
d
– 30,000 Volts
Glass Cylinder
c
Wire Mesh Cylinder
d
Pipe or Glass Cylinder
Gas
a
A
Glass Jar
b

FIG. 4

When the electrical circuit was open, and a gentle suction applied by means of a fan connected to the top of the apparatus, the light pieces of paper, tin-foil, etc., were lifted off the wire-gauze disk, and floated lazily along through the wire-gauze cylinder without any definite or prescribed course. Some of these particles jostled against their companions and aimlessly wandered along with the gentle current of air.

Upon closing the electrical circuit, however, these same floating or suspended particles evidenced a very distinct behavior; especially was this true between the wire *c* and the wire mesh cylinder. An immediate redistribution of the charges constituting the so-called neutral condition of these particles evidently takes place. In accordance with the laws which govern the action of such light bodies when brought into an electrical field, the particles almost invariably flocked very quickly toward the wire *c*, only to be hurled, as it were, away from it an instant later and start on their journey toward the wire-mesh cylinder, where the electric field was very much less intense.

Thus in Fig. 1, particles 1, 2, 3, and 4 have not yet experienced a redistribution of their charges constituting their neutral state. Particle 7 has its neutral state charges redistributed, and experiences an attraction toward the wire *c*. This particle will actually move toward *c* unless it is forced to move toward the wire-mesh cylinder due to collisions with its companions, which, like particles 5, 6, 8, and 9, have had the positive charges of their neutral states already neutralized by contact with or a near approach to the wire *c*, and then are hurled toward the grounded electrode or wire-mesh cylinder.

When such particles have once reached the grounded electrode, they sink more or less aimlessly down the inner wall of this electrode (provided they have not passed through the mesh), and finally reach the lower compartment *b*, where they may again be caught up with the ascending air current and repeat their experiences. The behavior of particles of finite dimensions, such as those described, is accounted for by the so-called polarizing action here described.

When other particles become of very small size, of ultramicroscopic dimensions, it is doubtful whether the polarizing action plays as prominent a part in the phenomena of electrical precipitation, as do the electron streams, or the coronal radiations and the accompanying secondary ionization which results.

In Fig. 2 the glass cylinder surrounding the wire-gauze cylinder of Fig. 1 was removed, and simultaneously with the application of a strong suction action at the top of the apparatus, a current of air laden with fine suspended particles was forced into the left end of the cross pipe *A*, as indicated by the arrow. The slight in-draft of air through the wire mesh prevents any appreciable passage of the suspended particles out through the mesh. As this experiment proceeded some of the particles carried in suspension in the gaseous stream were deposited, as at *a* and *b*.

Upon closing the circuit as in Fig. 3 a change quickly took place. The particles, which in Fig. 2 had been moving aimlessly along with the gaseous stream, were now acted upon by the electrical forces, because they were hurled bodily out through the wire mesh with considerable velocity, and to a distance of several feet. The polarity of those particles which had not collided with the grounded electrode, or otherwise given up their negative charges while they were passing through the mesh, was easily determined by the gold-leaf electroscope.

The general appearance was that shown in Fig. 3, in which scarcely any of the suspended particles, for the given suction draft, traveled far enough upward to reach the upper end of the wire-mesh cylinder, and this took place notwithstanding the in-draft of air through the mesh due to the suction action applied by the fan. In this case there was a noticeable increase in the deposit at *b*. Referring now to Fig. 4, the six-in. glass cylinder encloses the wire-mesh cylinder in the manner described in connection with Fig. 1. The circuit is closed as in Fig. 3, and the space between the wire-mesh cylinder and the enclosing glass cylinder soon becomes filled with the particles which have experienced a motion radially out from the wire *c*, under the action of the electrical field.

When the suction fan alone is used to draw the particle-laden gaseous stream through the apparatus, the suction velocity may be so adjusted that no solid particles are present in the air or gas delivered from the suction fan. When this is the case, the space between the wire *c* and the wire mesh becomes more and more cleared of suspended particles as the top of the apparatus is approached, and the density of the suspended particles deposited in the space outside the wire mesh is somewhat as represented by the depth of shading. Just as soon as this space becomes filled with solid particles, the continuance of this electrical action gives rise to a perfect shower of particles or aggregates of particles traveling down the inner wall of the wire-mesh cylinder, and passing right through the ascending particle-laden gaseous stream, they are deposited or precipitated as at *b*. Cold soot from soft coal, cold blast furnace dust, cement and alumina dust, and other fine particles have been tried, with almost identical results.

Fig. 5 gives the general form of the rectified current wave used in these experiments. The central parts of both lobes of the cycle were used and the mean value was between one and two milliamperes.

THE PRECIPITATION OF SMOKE, CEMENT DUST, ALUMINA DUST, ASHES, ETC.

In the non-conducting type of particles or at least those only slightly conducting, is included a large number, of which the above are prominent examples.

In the presence of intense electric fields, and apart from possible initial ionization due to high temperatures of the gases, or chemical action taking place at high temperatures, the ionization which takes place between the electrodes, due to electronic and ionic streams, would sweep the particles to that part of the field which is the weakest, or strongest, depending upon their specific inductive capacitances. This weakest part of the field is located at that electrode which has the larger surface, such as is the case of a cylindrical pipe within which is placed coaxially a wire of small diameter. For a given length of such a cylindrical pipe, the suspended charged matter in the gaseous stream which is made to pass through the pipe, in order to reach the inner wall of the pipe before it passes out of the electric field between the wire and pipe, must move with such a velocity lengthwise of the pipe as will allow it to move in the same time a maximum distance equal to the radius of the pipe. Under these conditions, heavy aggregates, which move more slowly than finer ones, require a longer pipe of the same diameter for the same pipe velocities.

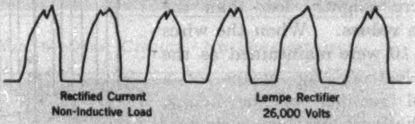


FIG. 5

A precipitator based on these principles was designed by Dr. Strong and the writer, and Figs. 6, 7, and 8 give the general appearance of the top of the outfit, when 900 cubic feet of coal smoke was moving through it at a velocity of about five feet per second. Two circular groups of eight and seventeen pipes respectively, each pipe four feet long, and five inches in diameter, are firmly jointed to two end headers, to which the fine wires are attached, to keep them in rigid position. Fig. 9 gives a sectional view of this precipitator.

While it is understood that ionic streams may be produced in varying degrees of intensity by point, brush, and corona discharges, it is with the last named type of discharge that this precipitator operates. The positive and negative corona discharges, respectively, between the wires and the pipes as the active and grounded electrodes, for still air, are represented in Figs. 10 and 11. The original photographs were taken at night with the precipitator placed horizontally and the voltages employed were slightly less than the breakdown values. When the wires as in Fig. 10 were maintained as the positive electrode by means of a mechanical rectifier of the Lempe pattern, the large patches or clusters of coronal glow, which constituted the positive corona discharge, occupied nearly the entire cross-section of the pipe.

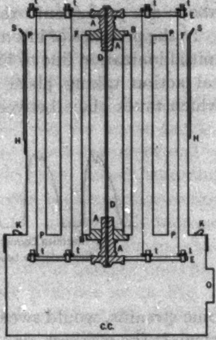


FIG. 9—PRECIPITATION CHAMBER

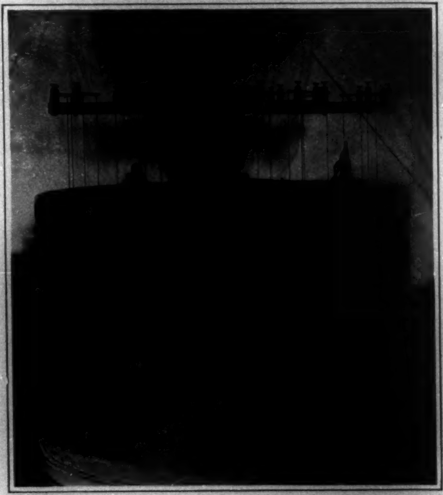
Fig. 11 shows the wire as the negative electrode. In this case the coronal glow is very limited in its depth radially, being at best only a few millimeters. Fig. 12 gives the appearance of the alternating-current corona.

Comparing the cleaning action of the positive and negative corona discharges with that due to an alternating corona, the following values give an idea of the relative efficiencies of the three kinds of discharges:

1. The alternating corona precipitates about 50 per cent of the suspended matter.
2. The positive corona precipitates about 70 to 80 per cent of the suspended matter.
3. The negative corona precipitates about 95 to 98 per cent of the suspended matter.

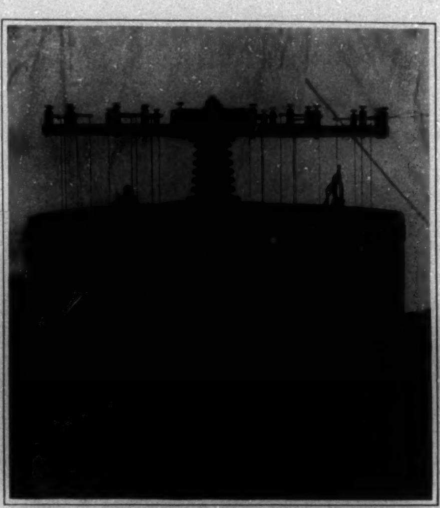
[NESBIT]

FIG. 6—OPEN CIRCUIT—NO PRECIPITATION



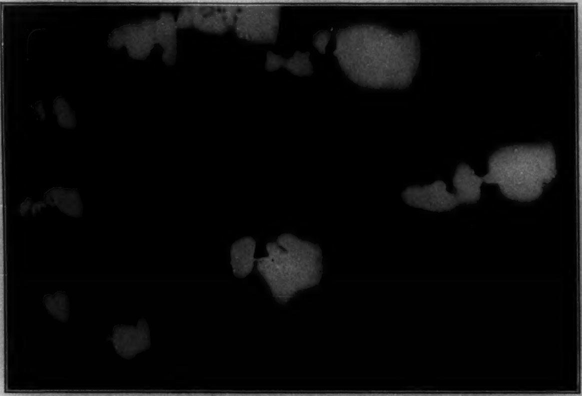
[NESBIT]

FIG. 7—TWO-FIFTHS SECOND AFTER CLOSING THE CIRCUIT



[NESBIT]

FIG. 8—ONE SECOND AFTER CLOSING THE CIRCUIT
98 per cent clearance

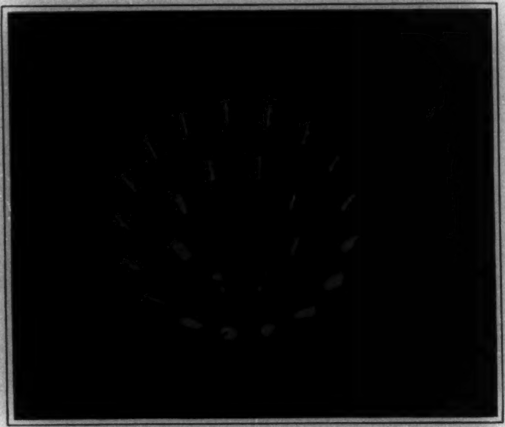


[NESBIT]

FIG. 10—POSITIVE CORONA IN CYLINDRICAL PRECIPITATOR

[NESBIT]

FIG. 11—NEGATIVE CORONA IN CYLINDRICAL PRECIPITATOR



[NESBIT]

FIG. 12—ALTERNATING-CURRENT CORONA IN CYLINDRICAL PRECIPITATOR

The unfitness of the alternating-current corona discharges arises from the fact that the reversal of the polarity of the active electrode, at which the field is very intense, results in a greater or less reversal of the direction of motion of the electrons and ions which are already on their journey toward the walls of the pipes. By this action many of the ions are more or less partially pulled back into the central region of the pipe, and before they ever reach the walls or an equivalent distance from the wire, the smoke or dust particles thus charged may have been carried out of the pipe and thus do not suffer precipitation. With hot air passing through the precipitator, and with a negative corona, the breakdown voltage is somewhere near 32,000. For cold air the voltage was slightly greater. With a positive corona the voltage was lower with both hot and cold air. Very little difference in the voltages, from those given for cold air, were detected in the use of cold smoke.

With smoke so hot that tar trickles down the central wire or active electrode, and also down the pipe walls, the voltage had to be decreased from 33,000 to about 28,000, in order to prevent violent disruptive discharges. Unless there is much moisture present, or the ingredients in the gaseous streams are sticky in nature due to their high temperature, there will be but little deposit on the electrodes. In any event, such a deposit suffers a tendency to be dislodged due to the slight vibration of the wire or the occurrence of a disruptive discharge of short duration. This variation in voltage must be brought about by a hand or automatic regulation, in a very short time, in order to avoid the establishment of an arc. If the impressed voltage is not too near the breakdown value, a disruptive discharge may continue for several seconds and then break, giving way again to the silent discharge.

The presence of fine points or irregularities on the inner walls of the pipes tends slightly to localize the discharge. Fine points due to hardened deposits, kinks in the wire, or rough spots on its surface very materially localize the discharge from the active electrode; and even though there may be many such local discharges, the cleaning action of such discharges is much below that of the perfectly uniform field about a smooth wire although it may have considerable deposit on it.

Smoke, or other suspended particles contained in the gaseous streams, passes with considerable freedom from being precipitated through the positive corona, the alternating corona, or the localized type of discharge.

With the cylindrical pipe type of precipitator described, about the same efficiency of cleaning was obtained for a number of materials, such as ashes, alumina and cement dusts, fine powdered clay, sand, and hot and cold smoke.

APPLICATIONS OF ELECTRICAL PRECIPITATION

A study of electrical precipitation processes and apparatus, applied to the cleaning of producer and blast furnace gases, is a field in itself of immense value to all interested in the steel industry. We must admit that proper methods of firing furnaces whether in power plants, mills, factories, or our homes, and either by hand or mechanical devices, will do a great deal to eliminate a large amount of our inexcusable smoke nuisance. However, there are many instances, where through limitations of furnace room space, equipment, etc., the furnace, fired by hand or by a stoker, is called upon to do a duty two or three times its normal rating. Under such conditions an electrical precipitation outfit might be of service either continually or at intervals, because it will precipitate the ash as well as the carbon particles.

The mechanical stoker, when properly used, eliminates very largely the carbon constituents of smoke by providing conditions of more perfect combustion, but it gives no aid in eliminating the discharge of ashes from the stacks of our mills and factories, or the chimneys of our homes. This item is one greatly in favor of the electrical precipitating processes when cleanliness as well as recovery of finely divided particles is the issue.

Other methods which are non-electrical, and which have found more or less favor in removing suspended matter from gaseous and fluid bodies are: (a) Settling. (b) Centrifugal. (c) Washing. (d) Filtering.

SUMMARY

Electrical precipitation may be accounted for by considering the phenomena of ionization, and the laws of electrically charged bodies.

A molecule or group of molecules of any substance in the neutral state constitutes a material system in electrical equilibrium under the action of its own component electrical charges and these component electrical charges are capable in an electrical field of becoming detached from each other and from the matter with which they are associated.

Nature furnishes, on an enormous scale, an illustration of the first steps in the electrical precipitation processes as well as the actual precipitation of suspended matter itself.

The addition of an electron to a molecule or a group of molecules, or a particle of finite size, such as a dust or smoke particle, gives rise to a negatively charged ion or negative aggregate, which will be acted upon by an electrical field.

When an electron has been removed from a molecule, a group of molecules, or a material particle, it gives rise to a positive ion, or aggregate, which, while it exists, will travel toward the negative electrode.

The size of the charge on the negative or positive ion depends upon the number of electrons which have been added to or removed from the molecule, group of molecules, or material particle.

Raising the temperature of a gas increases its electrical conductivity; a larger number of ions of one or both kinds is present, and these gaseous ions, independent of the ions which may be formed from matter held in suspension, serve as conveyers of electricity.

Ions may become the centers about which aggregates will be formed; and from this view-point we may account for the elevation of potentials by the forming of the aggregates, and the lowering of the potentials by splitting them up.

The principal ionizing agents are Roentgen and Becquerel rays, cathode and other rays, the electric field, heat, flames, ultraviolet light, and chemical action. The most prominent of these ionizing agents in electrical precipitation are heat, the electric field, cathode rays, and chemical action.

When the temperature is sufficiently high to produce a red or white heat the velocity of some of the electrons becomes so great that they are able to escape from the metal, thus all hot and incandescent surfaces become the seat of a more or less intense stream of electrons and positive and negative ions. This ionizing action of high temperatures has some effect on the migration velocities attained by the particles suspended in a gas, when they come into an electric field.

At low temperatures, gases, as well as their suspended matter, may have little or no initial ionization, consequently the electrical conductivity is practically the same in either direction, and the suspended matter suffers little or no tendency to travel in the direction of the field.

For equal flow of current through gases, between two electrodes, the relative dimensions and positions of the electrodes and their polarities, will determine the potential under which the electric field must be established to give the most efficient precipitation.

The electrical precipitation of suspended solid or liquid particles of the non-conducting type depends upon the intensity of the electric field, the quantity of gas to be treated and its temperature, the degree of initial ionization, and the type of corona discharge employed.

Very little if any difficulty is experienced in treating soft coal smoke if the temperature is low enough, and little or no deposit forms on the electrodes.

The use of the negative corona, while somewhat more difficult to maintain as judged by the coronal glow,—as the breakdown voltage is approached, is the most effective in precipitating particles in gaseous streams; and this is no doubt largely due to the high electronic and ionic velocities associated with this type of corona discharge, or electric discharge in general.

Any roughness or fine points on either of the electrodes of a precipitator tends to localize the discharge, and through such fields the particle-laden gaseous streams may pass without suffering precipitation of the suspended matter to the same extent as when the field is uniform.

Two important fields of application for electrical precipitation, provided the liabilities of danger are eliminated, are in connection with the cleaning of producer and blast furnace gases.

Electrical precipitation of soft coal smoke takes care of the ash as well as the carbon products.

Presented at the 3d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 19, 1915.

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PRACTICAL APPLICATIONS OF ELECTRICAL PRECIPITATION AND PROGRESS OF THE RESEARCH CORPORATION

BY LINN BRADLEY

ABSTRACT OF PAPER

The technical and financial progress made by the Research Corporation since its organization in 1912 is given, and several plants are described. Voltages, electrode spacings, power consumption, etc., are given for several installations. Mention is made of a number of improvements in the electrical apparatus and means for its control. Progress has been made towards standardization of apparatus for this work.

The paper is illustrated with reproductions from photographs of installations in various stages of operation. Curves and charts show the peculiar character of the circuit, the method of obtaining data to be used in designing precipitators and of conducting tests. Alternating current of 250,000 volts has been rectified and used for precipitating particles from gases. Fumes have been separated into fractions by means of temperature control and the electric processes.

A selected bibliography is included. The statement is made that within three years' time the original capital of $10,100 has been paid back to the stockholders, and that a fund of over $150,000 has been accumulated from the corporation's work, to be used for scientific research.

IN CONNECTION with the development and administration of processes for removing from gases finely divided particles suspended therein, the Research Corporation has not only devoted considerable time and effort to a consideration of the theories, but also has endeavored to adapt them successfully to a great variety of practical conditions, and to further strengthen and standardize the art. The history and theories of electrical precipitation have been described elsewhere,* so it is not necessary to review them in this paper, and moreover, it is undesirable to do so because of the wide field to cover in recording the practical and commercial results already achieved.

The article by Dr. F. G. Cottrell, appearing in the annual report of the secretary of the Smithsonian Institution for the year 1913, gives an excellent outline of the work up to the time when the report was prepared. The present paper aims to

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***See selected bibliography at end of this paper.**

cover broadly the work to date, including many things not given in previous articles.

The task of solving the numerous technical problems encountered has been so exacting of time and effort that heretofore it was considered best to refrain from publishing the results of the work and information as to our progress until the processes had been proved and the organization and financial position of the corporation were advanced sufficiently to insure its commercial stability. The invitation to present a paper was finally accepted not only because sufficient progress of a very definite nature had been made to warrant some statements, but also because a report upon the progress and developments would prove to be interesting and valuable to members of this Institute.

The experimental work and the theoretical phases of electrical precipitation are replete with many interesting facts—and also with apparent facts; it is these latter which sometimes prove to be dangerous pitfalls. The difference between a successful and an unsuccessful installation is often very slight from an electrical engineer's point of view, whereas the various other chemical, metallurgical and mechanical engineering features are often much more difficult of solution. Partly for these reasons we consider that the knowledge and experience, gained through close association with a wide range of practical applications, are among our greatest assets. Of course it is to be expected that improvements and refinements will continue to be made from time to time, but it hardly seems likely that radical departures from present fundamentals will be made in the near future. As is usual in all pioneer work, the valuable theories and formulas will probably follow the practical application.

Probably a great majority of the Institute's members are aware that high-potential electricity was employed for depositing or condensing particles suspended in gases many years ago, and that the accompanying phenomena could readily be demonstrated in the physicist's laboratory. Nevertheless it is a fact that use of the high-tension electric field for this purpose was not made commercial until in recent years, and that full credit is due Dr. F. G. Cottrell for having made this possible. In this connection the following remark is pertinent to a comparison of theory and industrial application. A well-known chemical engineer, who invented some valuable processes and has made them commercially successful, has stated that after one has completely solved all of the problems which it is apparently possible to solve in a laboratory, and has obtained comprehensive patents and has thoroughly studied the conceivable theories, and is therefore likely to consider his work almost finished, he is rudely awakened when confronted with the cold, hard fact that fully 90 per cent of the real work remains to be done. It may not be possible to estimate a similar relation between theory and practise in connection with electrical precipitation, but it is certain that the practical and commercial end has demanded an enormous amount of time and effort. The variety of problems and conditions, in connection with which requests have been made for application of the processes, has been very extensive, as one can readily observe from the information given in a later part of this paper. Nearly every problem which has been investigated by us has required that engineers of our staff not only fully understand our own processes but also be well acquainted with other details of the operations conducted at the plant in question.

The Research Corporation was organized in New York City early in 1912, one of its specific duties being to administer the electrical precipitation patents assigned gratis to it by Dr. F. G. Cottrell and his associates, E. F. Heller, Edmund O'Neill, and H. E. Miller. The reader is referred to Dr. Cottrell's articles for the details of the gift and the corporation's purposes and aims.* The total capital paid into the treasury was $10,100, out of which all expenses for organization, office equipment, salaries, etc., had to be paid until income was obtained from the practical application of the processes. Since the stockholders were prohibited from ever obtaining any profits from their holdings, it was considered unwise to administer the work along lines which might compel the corporation to request more subscriptions to its stock. Also, for similar reasons, our operations were so conducted that no financial obligations would accrue to either the stockholders or the directors. Therefore, one of the requirements of our early contracts was that the client had to pay all expenses incident to our work upon his problem, and in addition thereto had to pay us certain stipulated sums of money for technical services. While this was not the ideal arrangement, nevertheless it should be realized that the adoption of this policy made it possible to prove and stabilize the process without resorting to the further sale of shares of stock. This latter feature was especially desirable because the founders of the Research Corporation, and especially Dr. Cottrell, desired to demonstrate and to emphasize the fact that a large sum of money was unnecessary for establishing the corporation and making it a financial as well as a technical success. Another idea was that the industries benefited by the work of the corporation should contribute to the support of such an altruistic movement. Results have amply proved the correctness of these contentions and all parties who have assisted so earnestly and ably are entitled to hearty thanks for their generous support.

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*See selected bibliography at end of this paper.

The technical situation in the electrical precipitation field in March, 1912, was about as follows:

A commercial installation was precipitating sulphuric acid mist at the Selby smelter in California,* having been in successful operation for at least two or three years. This installation was designed and its construction supervised by Dr. F. G. Cottrell, assisted by Mr. H. A. Burns. It has been in steady operation ever since.

Another installation had been made for handling lead roaster gases at the Selby smelter, but it was not continued in operation, due primarily to the fact that the farmers still complained of the sulphur dioxide which passed through the treaters as a gas, and of course could not be removed by this process.

Some experiments* had been conducted by Dr. Cottrell, assisted by Mr. Burns, at the Balaklala smelter in Shasta County, California, and a large installation had been subsequently made for treating all the gases passing through the main flue. The smelter was shut down and abandoned, pursuant to a court order obtained by the farmers and likewise based on the sulphur dioxide concentration in the stack gases. Before final testing and adjustments had been made this installation removed from 80 to 90 per cent of all solids and it is reasonable to expect that this percentage could and would have been increased considerably had operations continued. Recent experience with similar problems certainly warrants such a statement.

Mr. Burns had superintended some experiments in a sulphuric acid plant at Bayonne, N. J., the object being to remove dust from the hot burner gases. Experience with details of the processes was far more limited then than now and the tests were discontinued before conclusive results had been obtained. It may be of interest to note that we recently undertook this same problem at another plant with successful results, so that a commmercial installation is now to be made. The difference between the results in the respective cases was due more to mechanical reasons than to any inherent features of the electrical precipitation processes.

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*See selected bibliography.

Dr. Cottrell and his associates had successfully employed high-potential electricity for separating emulsified water from California crude oil, but as these patent rights are not a part of the Research Corporation's holdings, no further mention will be made of them in this paper.

Mr. Walter A. Schmidt* had undertaken to adapt the electrical precipitation processes to the collection of cement dust at the Portland cement plant near Riverside, California, and early in 1912 had made excellent progress, having up to that time installed one complete precipitator handling the gases from one rotary cement kiln. Ten units are now in continuous operation at that plant, collecting in the neighborhood of 100 tons of dust daily.

After experimental work had progressed satisfactorily at Riverside, and the Balaklala smelter had ceased operating because of the sulphur dioxide controversy, Messrs. Howard and Rathbun, and later, Mr. Barker, conducted experiments with the electrical precipitation processes at the Garfield smelter of the American Smelting and Refining Company, the immediate problem being to remove the solids from the gases coming from copper matte converters. These gases carry a considerable quantity of lead compounds together with other metal values, the principal object of the fume collection being to save these values. When the Research Corporation was organized, the work at Garfield was still in the experimental stage. During the summer and fall of 1914, a large installation at Garfield was completed and the entire volume of converter gases is now being successfully treated, with a reported collection of over 95 per cent of the suspended matter. The Garfield installation is in the territory controlled by the Research Corporation.

The above condensed record shows the extent to which the electrical precipitation processes had been developed when work was started in the eastern part of the United States by the Research Corporation.

It seems strange, at first thought, that the electrical precipitation processes were first successfully used in a commercial way for the precipitation of sulphuric acid mist, which had previously been, and even to this date is, one of the most difficult materials to collect by ordinary methods. This mist, which consists of extremely small drops of sulphuric acid, generally containing some free water, is handled with comparative ease by the electrical precipitation processes.

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*See selected bibliography.

The following brief statement is made at this point for the benefit of those who may not be fully informed as to the fundamental methods employed in electrical precipitation. To remove from gases either solid or liquid particles carried in suspension therein, the present method is to subject the gases and suspended particles to the action of a strong electric field maintained between so-called "collecting electrodes" and "discharge electrodes," the latter being insulated from the former and connected to a suitable source of high electric potential. Alternating current fails to give the kind of field most desired, therefore the polarity of the electrodes is kept fixed, the current flowing between them through the gases being unidirectional. This is accomplished in practise by stepping up single-phase alternating current to an effective potential of say 75,000 volts, then changing this high-potential alternating current to high-potential unidirectional current by means of a suitable rectifier and delivering the rectified current to the discharge electrode of the precipitator. The gases are rapidly ionized and the suspended charged particles under the action of the electrostatic field are forced to the collecting electrodes. Maintaining the discharge electrodes negative with respect to the collecting electrodes is the general practise. By use of a specially designed rectifier 250,000 volts a-c. has been successfully rectified and efforts are now under way to raise this figure to a much higher value. However, the difficulties encountered in handling such pressures are so many that they may not come quickly into commercial use, at least in the immediate future.

The potential difference between electrodes up to 1912 seldom exceeded 50,000 r. m. s. volts. In some instances the potentials employed were relatively low and a brush discharge or corona was not readily obtained unless a pubescent surface was employed. This type of discharge electrode is used at present in certain cases, but in most of the problems it is not considered necessary because of the higher potentials now in general use.

The electrical equipment must be of such design and construction as to be suitable for the circuit conditions peculiar to the process and must be compact, economical and fool-proof. The precipitator proper, which contains the discharge electrodes and collecting electrodes past which the gases travel, must be of such material and construction that corrosive gases, if present, cannot injure it. It is good practise to design the precipitators of ample proportions, with ready access to the electrodes and insulators, and with due regard to the methods of conducting the gases into and out of it and to the location of flues, furnaces, stacks, buildings, etc. Under some circumstances it is desirable to treat the gases while traveling horizontally, while in others a vertical gas flow should be adopted. Sometimes special types of electrodes must be employed, but the variety of problems and conditions is so great that it is not considered desirable to endeavor to prescribe any general rules in this regard.

The precipitators must be so arranged that the dust, fume or liquid may be readily removed after deposition. In some problems a leakage of air into the gas to be treated is not harmful, while in others, such as the cleaning of burner gases in sulphuric acid manufacture, dilution due to air "inleakage" is objectionable.

A partial record of the results obtained since 1912 is given below.

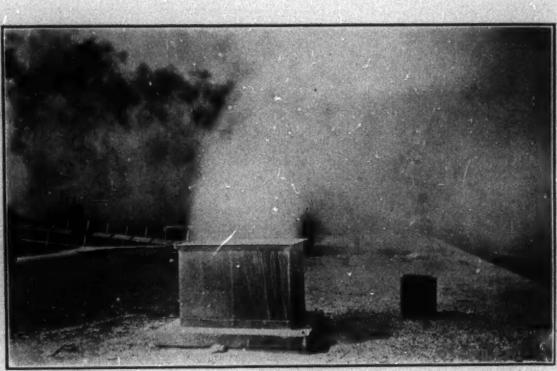
The first problem undertaken by the Research Corporation was to recover the valuable fumes from silver refinery gases at the Raritan Copper Works, Perth Amboy, N. J., after they had passed through a water scrubber which was supposed to recover practically all of the values. In this installation very corrosive gases were encountered. Many materials of construction were experimented with—even ductile tungsten, which at that time (1912), was not readily obtainable. The construction problem was finally solved by the use of heavy cast iron in parts and a mixture of lead and antimony for other parts. Insulation and draft troubles were also encountered but they were finally overcome, with the result that the installation has already saved several thousand dollars' worth of valuable fume. The power consumption is about 2.5 to 3 kw. and the voltage averages about 35,000. Recently an additional precipitator unit with 18-in. diameter pipes as collecting electrodes was installed. This operates very successfully and marks a distinct advance over the old type of precipitator in several respects. The electrical equipment used in connection with this new unit consists of a 10-kv-a. motor-generator set, a 10 kv-a. 25-cycle single-phase, 100,000-volt transformer and a large rectifier. Occasionally some of the deposited fume, which is a good conductor of electricity, drops between the electrodes and draws a heavy arc. This used to cause the automatic circuit breaker to open and an auxiliary circuit to ring a bell and notify the attendant. A relay panel has been developed which prevents frequent tripping of the breaker by automatically introducing resistance in the low-tension circuit upon the occurrence of an arc in the precipitator. This device has rendered operation much more continuous and has therefore increased the values recovered.

Considerable work has been done at the plant of the Balbach Smelting and Refining Company, on gases from cupel furnaces. Satisfactory results have been obtained in tests conducted with a small precipitator, and a large installation to handle the entire volume of gases will be installed in the near future. The volume of gas to be treated is about 10,000 cu. ft. per min.; 12-in. diameter pipes, 20 ft. in height, will be used for collecting electrodes and No. 10 jack chain for discharge electrodes.

Opinion was widely divided as to the probability of successfully adapting the processes to Waterside station No. 2 of the New York Edison Company, the problem being to remove cinders from the boiler plant gases. Nevertheless, for various reasons, efforts were made, and the conclusion was reached that there was not sufficient available space for precipitators in the building to insure successfully treating all the gases, especially without imposing prohibitive restrictions upon the draft. Tests with a small precipitator showed that the cinders could be removed while moving at a velocity between 5 and 10 ft. per sec. without using water and that they could be precipitated at a considerably higher gas velocity when water was used.

Our tests at the plant of the Orford Copper Company, on a small scale, were successful. Various kinds of gases were treated and many data obtained which will be useful if a large installation is made. The various flues, stacks, etc., were studied and plans and specifications for equipment to handle all the gases were prepared and submitted with our report. The values recoverable from the gases apparently are not sufficient to warrant the heavy installation expense; therefore, before deciding to incur the financial risks incident to such a large installation, especially when only an alleged nuisance was involved, it was decided to await further developments. It is quite possible that a large installation will eventually be made at this plant.

At the plant of the Hooker Electrochemical Company, a large



[BRADLEY]

FIG. 1—EXHAUST FLUE FROM THE TREATER AT THE HOOKER ELECTROCHEMICAL COMPANY'S PLANT AT NIAGARA FALLS, N. Y.—VOLTAGE OFF.

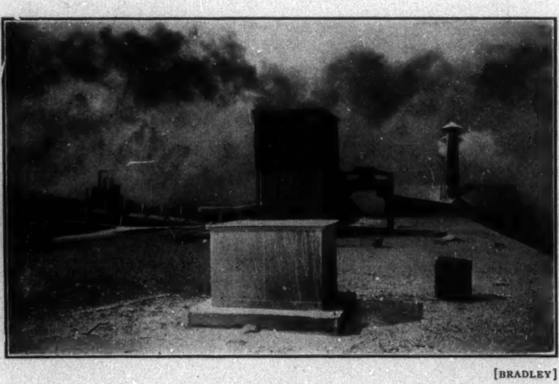


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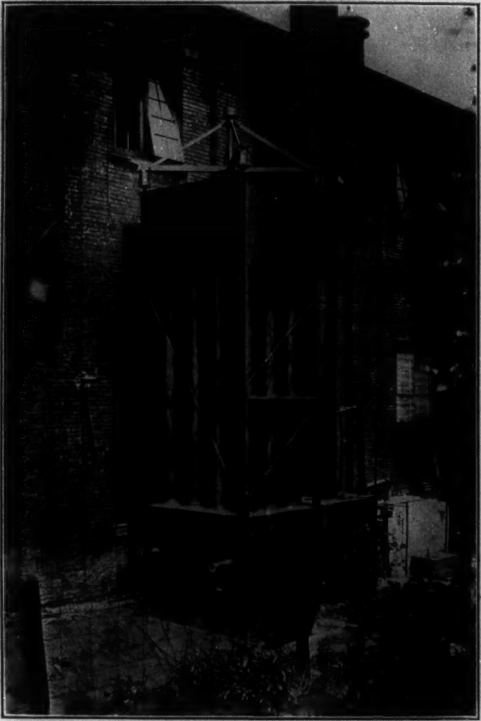
FIG. 2—EXHAUST FLUE FROM THE TREATER AT THE HOOKER ELECTROCHEMICAL COMPANY'S PLANT AT NIAGARA FALLS, N. Y.—VOLTAGE APPLIED



[BRADLEY]

FIG. 3—BUREAU OF MINES TREATER—PITTSBURGH, PENNSYLVANIA

PLATE XXII.
A. I. E. E.
VOL. XXXIV, 1915

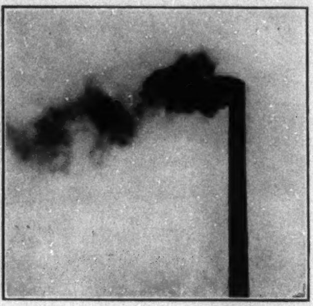


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FIG. 4—TOP OF STACK—BUREAU OF MINES TREATER, PITTSBURGH, PA.—VOLTAGE OFF

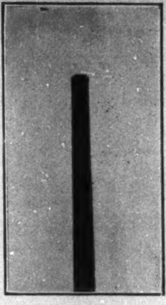

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FIG. 5—TOP OF STACK—BUREAU OF MINES TREATER, PITTSBURGH, PA.—THIRTY SECONDS AFTER APPLICATION OF VOLTAGE TO TREATER

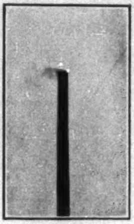

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FIG. 6—TOP OF STACK—BUREAU OF MINES TREATER, PITTSBURGH, PA.—SEVERAL SECONDS AFTER VOLTAGE IS CUT OFF

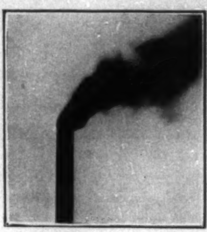

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FIG. 7—TOP OF STACK—BUREAU OF MINES TREATER, PITTSBURGH, PA.—VOLTAGE OFF

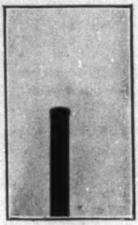

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FIG. 8—TOP OF STACK—BUREAU OF MINES TREATER—PITTSBURGH, PA.—VOLTAGE ON

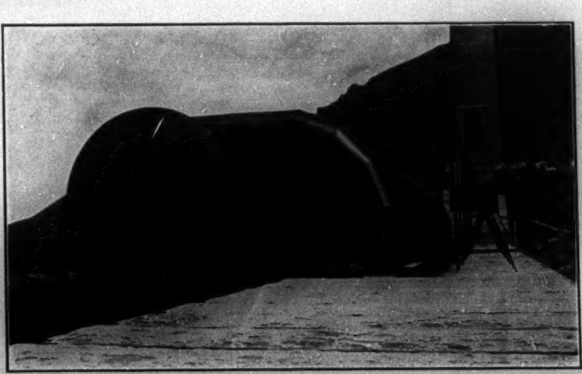
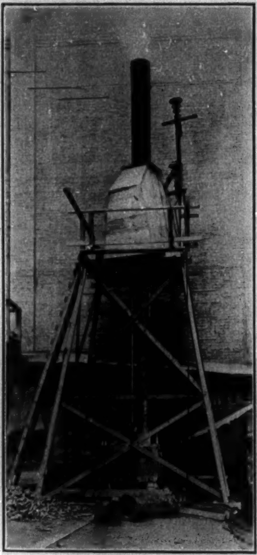
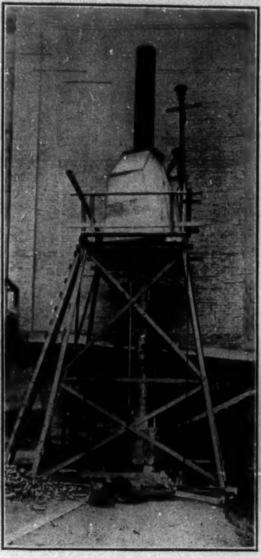


FIG. 9—GENERAL VIEW OF TREATER AT GARFIELD, UTAH [BRADLEY]



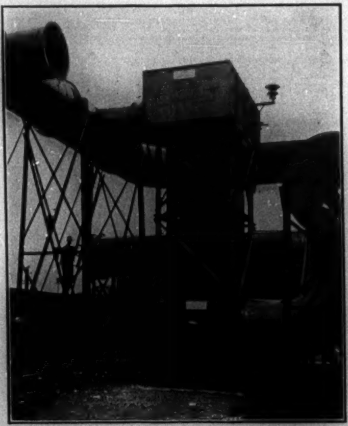
[BRADLEY]

FIG. 10—EXPERIMENTAL TREATER AT TOOELE—VOLTAGE OFF



[BRADLEY]

FIG. 11—EXPERIMENTAL TREATER AT TOOELE—VOLTAGE ON



[BRADLEY]

FIG. 12—TREATER FOR GOLDSCHMIDT DETINNING COMPANY

volume of air, containing a small percentage of chlorine gas, is treated for the removal of the latter. Hydrated lime dust is used to assist in the removal, and a few tons per day of weak bleaching powder are collected. The volume of gas is about 30,000 cu. ft. per min., with a power consumption of from 3 to 5 kw. Weak bleaching powder, chlorine gas and hydrochloric acid are not conducive to a simple insulation problem, as can readily be imagined; nevertheless it was successfully solved, and for potentials as high as 50,000 volts. In this case our most difficult problems have not been concerned specifically with the electrical processes, but, on the contrary, have been to obtain a steady introduction of hydrated lime into the gas.

Tests have been conducted on the gases from a hand-fired 80-h. p. boiler at the U. S. Bureau of Mines, Pittsburgh, Pa., for the elimination of black smoke. The removal of the smoke particles is accomplished quite readily, but the question of the removal of the collected soot from the electrodes is still under consideration and some further tests are to be made. As is to be expected, the results obtained thus far indicate that it is best to prevent formation of smoke whenever feasible, and not adopt methods for collecting it. But it should be noted that there are many places where, for local reasons or for immediate economy, it would be advantageous to install the electrical precipitation processes. The precipitator at the Bureau of Mines has twelve iron pipes 12 in. in diameter by 12 ft. long, through which the gases pass. The high-tension electrodes are wires hung in the vertical axis of the pipe. A pressure of about 50,000 volts is used, and the power consumption is approximately one kw.

Fig. 3 is reproduced from a photograph which shows the general arrangement of the treater.

Figs. 4, 5, and 6 show the effect of the electric field upon the smoke, the first showing the effect when the electric circuit is open, while Fig. 5 shows conditions 30 seconds after the voltage has been applied. Fig. 6 plainly illustrates how the smoke began to show itself at the stack top when the circuit was opened. Figs. 7 and 8 show the voltage off and voltage on. Mr. A. F. Meston had charge of the details of this installation.

The treating of gases from sintering machines and roasters at Salida, Colorado, was considered, but the tests made in the latter part of 1912 did not indicate that the values in the gases at the time were sufficient to warrant the expense of an installation. The plant management had been endeavoring to reduce their lead losses to a minimum by close chemical control of the material fed to the furnaces. Recent developments have so reduced installation costs that the problem may be reconsidered, especially since the processes are now in successful use on similar gases at another lead smelter.

Tests were conducted on a small scale at the Kings County Foundry with results showing that complete recovery of the fume was feasible. The gases come from cupola furnaces in which old tin cans and other metal scrap are reduced to a poor grade of iron which is made into sash weights. The fumes consist mostly of tin, lead and zinc oxides and the quantity per day is considerable. The cost of separating and refining the metals, when they are in the proportion as shown by analyses of the collected material, is such that the expense of the installation has not yet been incurred by the compnay which proposed to operate it, and therefore the scheme has remained dormant, since the completion of our tests and submission of our report. When a process has been perfected for treating these fumes economically so that the tin, lead and zinc can bring something close to their market value, the field is a good one in which to build up another by-product industry. As these sash weight foundries are operated at present it would be necessary to install a fairly extensive system for cooling the gases down to a reasonable working temperature. Of course, such apparatus increases the cost and helps to make difficult the profitable collection of these fumes at the present time.

Elaborate tests upon gas volumes, composition, temperature, fume content, etc., were conducted for the Chase Rolling Mill Company in order to secure reliable data upon which to base designs for full-scale commercial installations. The fume is mostly zinc oxide originating at the crucibles in which zinc and copper alloys are produced. Many tests were conducted with the electrical processes while the gas conditions were varied as to velocity, temperature, etc. The results were very gratifying, showing that the financial returns would warrant an installation. Plans have been prepared for large commercial installations at various locations and a contract for one of these has been awarded. Early in the testing work at this plant such discouraging results were obtained that some of our own men considered it to be a hopeless task, and it was with great difficulty that they were induced to renew the work and carry it to the favorable stage at which it is now. The management of the plant kept its faith throughout the trying periods when tangible results seemed to be the exception, and its course is to be commended. Mr. P. E. Landolt had charge of the details of the work at this plant.

Professor A. H. White has succeeded in cleaning the entire make of illuminating gas at the plant of the Ann Arbor Gas Company by means of the process, the installation requiring a very small amount of power. The tar removal was practically complete. At times during the testing period the gas velocity past the electrodes was over 30 ft. per sec. The installation is very simple and compact, and judging from his reports, should warrant its rapid and general adoption as standard equipment for this purpose in gas manufacture. Prof. White's work is described in the *American Gas Light Journal* for Sept. 21, 1914.

An installation at Omaha, Nebraska, for collecting sulphuric acid mist arising from so-called "parting kettles" in a silver refinery, practically identical with the Selby, California, installation, was also very successful. Mr. H. A. Burns had charge of the details of this installation.

The installation at Garfield, Utah, is fully described by Mr. W. H. Howard in the *Bulletin* of the American Institute of Mining Engineers, August, 1914. It consists of seven units, each of 360 five-in. pipes, 2520 in all. The volume of converter gases treated is approximately 200,000 cu. ft. per min. The collected material is quite high in lead, and several carloads have already been shipped for refining. It is a large, well-constructed installation and is reported operating very successfully, the collection being about 95 per cent of total solids. Semi-commercial tests also were conducted upon main flue gases, coming from blast furnaces, roasters and reverberatory furnaces. These tests likewise were successful and eventually these gases also may be treated by the processes.

The electrode spacing is 2.5 in., the potential about 30,000 volts, and the power consumption approximately 50 kw. The building which contains the motor-generator sets, rectifiers, control apparatus and switchboard panels is one to be proud of. Mr. Howard was assisted by Mr. R. F. Barker, to whom the details were delegated.

Fig. 9 gives a general view of the treater. The converter gases, mixed with more or less air, come from the converter building through a long steel balloon flue, drop a considerable amount of the heavier particles throughout the length of the flue, then enter the bottom header, pass upward through the five-in. pipes, into the upper header, then through the long radius pipes into the main flue, which also carries gases from other parts of the smelter. The photograph was made prior to actual connection of the flue to the new stack which is in the right background.

The small precipitator used early in the testing work at Garfield was subsequently shipped to Murray, Utah, and tests were conducted at the lead smelter with excellent results. The smelter already was equipped with a large and expensive baghouse, and for this reason it was not necessary to install the electrical processes immediately. The analytical results showed nearly 100 per cent clearance of the suspended particles of fume and acid.

At Tooele, Utah, small-scale tests were conducted on gases from sintering machines, carrying large amounts of lead, elementary sulphur, etc., and upon gases from roasters, converters and blast furnaces. In all cases the results were satisfactory. Two large units are now in successful commercial operation on the sintering machine gases and it is planned to install several others on these gases as soon as possible, and later to install precipitators on other flues at this plant as well. Each of the two units contains 48 pipes 12 in. in diameter by 15 ft. long, placed vertically. The electrode spacing is six in., the volume of gas treated is approximately 20,000 cu. ft. per min., the power consumption measured at the transformer at present is less than five kw., and the recovery of fume, when the treaters are not overloaded by forcing the blowers at the sintering machines, is practically complete. The fume contains a fair percentage of elementary sulphur, which formerly wrought havoc with baghouse installations, especially when it exploded. The potential on the treater, as indicated by transformer ratio and primary voltage, is about 70,000 volts. At this plant also some changes in the metallurgical operations have resulted in a considerable reduction of the values lost in the fumes, hence the electric processes are not called upon to recover as much as was being lost a year or so ago. Figs. 10 and 11 picture the small precipitator operating on these gases, and show the effect produced by the current. Mr. H. A. Burns has directed the detail work connected with the processes at this plant and he has been ably assisted by the smelting company's technical men.

Without having conducted any preliminary tests, a full-scale precipitator was designed and placed in operation for the Gold-

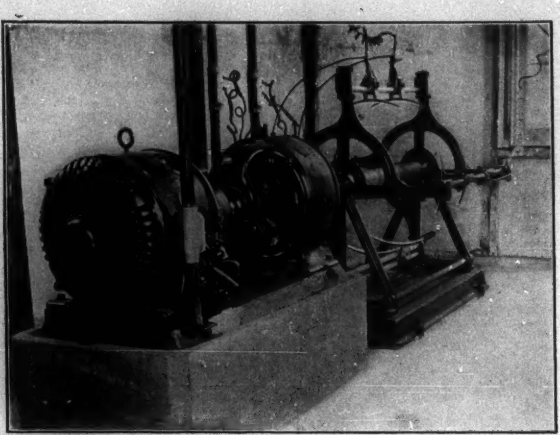


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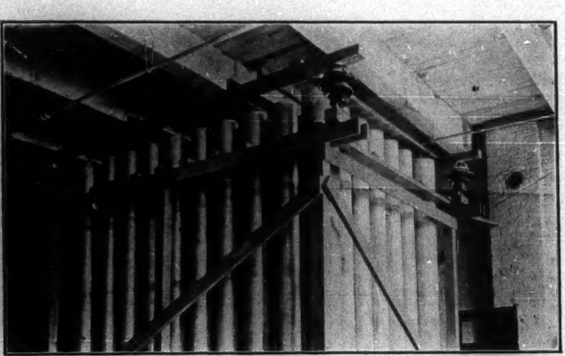
FIG. 13—PORTION OF THE ELECTRICAL EQUIPMENT FOR GOLDSCHMIDT DETINNING COMPANY



[BRADLEY]

FIG. 14—GENERAL VIEW OF TREATER FOR MILK FLOUR COMPANY (LOCATED IN A LOFT BUILDING)

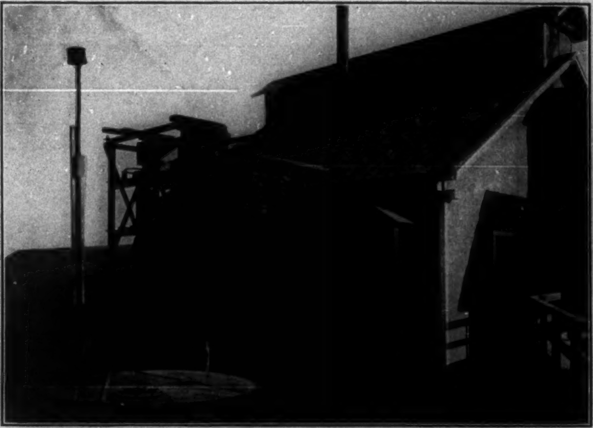


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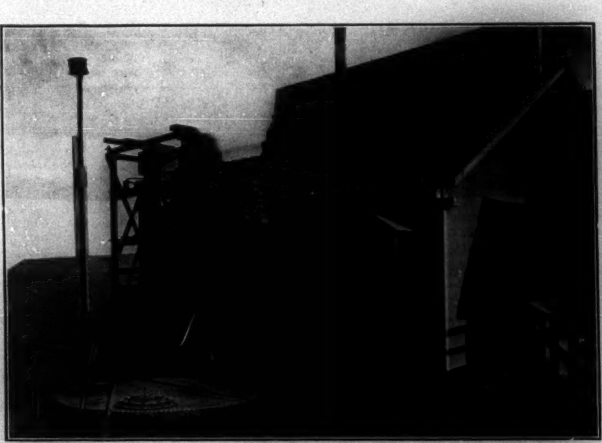
FIG. 15—EIGHTY-TON LEACHING PLANT ELECTRICAL FUME PRECIPITATOR CURRENT ON



[BRADLEY]

FIG. 16—EIGHTY-TON LEACHING PLANT ELECTRICAL FUME PRECIPITATOR CURRENT OFF

schmidt Detinning Company. The necessary alterations were very few and unimportant before a complete recovery of the tin compounds was being effected. The temperature of the gases sometimes reaches 800 deg. fahr. in the precipitator itself. Occasionally the white fumes and black coal smoke alternate. One can then observe the successive layers of white and black fume precipitated upon the electrodes and by this means can determine if the gas velocities in all compartments of the precipitator are practically equal. There are nine 12-in. iron pipes, the voltage ranges from 60,000 to 80,000 volts and the power consumption is from 600 to 1500 watts. Figs. 12 and 13 show a precipitator and some of the electrical equipment.

An inexpensive precipitator was installed for the Milk Flour Company, which is used for precipitating powdered milk, sugar, eggs, malt, grape fruit juice, etc. The powders are obtained from an evaporating plant wherein solutions, emulsions, etc., are deprived of their water content by spraying the liquid into a current of hot air. The powder is removed from the gas before it cools sufficiently to allow deposition of the evaporated moisture. Excellent powdered organic materials are recovered in this manner at a small expense. A small electrical precipitator was subsequently installed for removing dust from the air entering the evaporators, thus insuring a food product free from dirt. Fig. 14 is a general view of the precipitator.

A precipitator was installed at the Washoe Smelter, Anaconda, Montana, to be used for removing valuable metals and acids from gases arising from a modified MacDougal roaster, in which the Anaconda tailings were being subjected to an oxychloridizing roast. (*Bulletin* of A. I. M. E., August 1914.) The gases at that time were being passed through a scrubbing tower without obtaining a complete recovery of the values. The electric apparatus and treater were quickly erected and tried out, but at first with what were apparently unsatisfactory results. As similar phenomena had been encountered elsewhere, it was soon possible to show that the cloud emerging from the treater was due to moisture being condensed from the gaseous to the liquid condition when the escaping gases mixed with the cold air. It was also noted that if the furnace fires were poked so as to produce black smoke, no black could be discerned in the cloud above the precipitator when the electric current was on, but this was plainly visible when the circuit was opened—the difference between the white cloud (current on) and the dark gray cloud (current off) being very pronounced, thus giving a good indication that all solids were being collected. The temperature of the gases going to the precipitator was thereupon so reduced that no cloud would result after the gases had passed through. The results then showed a complete clean-up when the current was on and a dense white cloud above the precipitator when it was off. Some photographs were taken to show the effect and also the suddenness with which the electricity produced it. Some very good moving pictures of these fogs or clouds and their elimination were made at this time. Twelve-in. diameter lead pipes, 20-in. diameter wood stave pipe, and 24-in. diameter stoneware pipes were tested and all proved successful. It was interesting to view the tops of the pipes while in operation. One could see an absolutely clean gas immediately above the pipe outlet and it could be readily observed how the fog was produced in a manner similar to the cloud formation when exhaust steam leaves a locomotive stack on a cold and humid day. The name " tea-kettle effect " has been suggested for lack of a more appropriate and shorter term.

Examples of this effect have been frequently noted during tests elsewhere. The amount of " mist " formed after the gases were discharged from the precipitator varied with the temperature and humidity of the outside air. A typical calculation of such a condition will illustrate this point:

In a test treater handling 1800 cu. ft. of air per min., at a temperature of 152 deg. fahr., or 117 lb. of gas per minute, the air is saturated at 152 deg. fahr. (standard barometer) and carries 0.224 lb. of moisture in the vapor form per pound of air, or a total of 26.2 lb. of moisture per minute.

Assuming an outside air temperature of 42 deg. fahr. and 60 per cent saturation, and a sudden cooling of the discharged air to 52 deg. fahr. by mixing with the outside air, the heat transfer is as shown by the following equation:

$$(117) \times (0.24) \times (152^\circ - 52^\circ) + (26.2) \times (0.46) \times (152^\circ - 52^\circ) = (X) \times (0.24) \times (52^\circ - 42^\circ)$$

Where the specific heat of the air = 0.24

the specific heat of the water vapor = 0.46

X = lb. outside air per minute necessary to be mixed with the discharged air (neglecting radiation) to effect the cooling to 52 deg. fahr., and equals 1670 lb., then the amount of moisture per lb. mixed discharged and outside air is

$$\frac{1670 \times 0.0056 \times 0.6 + 26.2}{1670 + 117} = 0.0179 \text{ lb.}$$

But the saturation point of air at 52 deg. fahr. = 0.008 lb. moisture per lb. air, so a " mist " or " fog " will form just above the top of the pipes.

This " fogging out " has been encountered repeatedly in practise. When tests are made during the winter season, a visible mist is formed after the gases are discharged from the precipitator, when warm saturated gases are being handled. During the periods of dry and warmer weather, the " fogging out " is greatly decreased.

In other cases, where the temperature of the discharged air, saturated with moisture, is only a few degrees above that of the outside air, no mist or fog is produced. It is possible to predict from calculations made in a similar manner whether or not a mist or fog will be produced under any given conditions.

It is further possible to show by calculations whether mixing two or more gases, varying in temperature and in percentage of saturation, in given proportions prior to passing through the precipitator, will avoid this formation of a mist or fog, when the discharged gases mix with the outside air.

The processes were used for some time at Anaconda to check up the furnace losses, as they could be depended on to precipitate all solid matter in the gases. Plans were being prepared for a large installation at the proposed leaching plant, but later improvements in roasting and leaching made it unnecessary to add salt to the roaster and this in turn reduced the losses to such an extent that it was considered unnecessary to recover the fume.

Immediately after the leaching plant tests had been concluded an installation of the processes was made at the arsenic plant, where flue dust is roasted to remove the arsenic from the metal values, and then the concentrated arsenic is recovered and refined. The plan was to separate the mechanically carried impurities from the gases at a high temperature, next cool the gases so as to condense the pure arsenic, and then recover it directly, thus saving a second refining.

This was the first really serious effort made to use electrical precipitation as an adjunct in fractionating components of fume, although some previous attempts had been made at Perth Amboy, N. J., in our work there on the silver refinery fumes. The results at the arsenic plant showed conclusively that it was a feasible method and after sufficient data had been obtained, a commercial installation was designed and started. Construction work was suspended on account of the situation resulting from the European war and this installation has therefore not yet been completed; although reports state that it is now going forward.

Messrs. Elton, Dunn,* Kellogg and Mitchell have been handling the work at this plant during the latter period. They have also tested the processes on a semi-commercial scale on the gases from the blast furnaces, converters and roasters, and have obtained satisfactory results. They have even exceeded in size the three-ft. pipe originally installed at the arsenic plant, by using an iron pipe four ft. in diameter as the collecting electrode, and a 250,000-volt transformer and mechanical rectifier to correspond.

Treating the enormous volume of gases in the main flue at Anaconda presents several problems. In addition to magnitude, there are numerous problems connected with the handling of the fumes and dust and their metallurgical treatment, so that it will be some months at least before any very definite progress can be reported. However, the results thus far obtained were so encouraging that the smelting company purchased a license for the use of the processes throughout their plants at Tooele, Great Falls and Anaconda, and they are now in a position to make rapid progress with their installations. Figs. 15 and 16 show the experimental leaching plant at Anaconda and the electric precipitators under various conditions of operation. Figs. 17 and 18 show how completely the fume is precipitated by the electric processes, the views showing respectively the "voltage on" and "voltage off" effects. The fume contained, among other things, hydrochloric acid, sulphuric acid, dissolved sulphur dioxide, carbon, compounds of copper, silver, iron and arsenic. Figs. 19 and 20 show the rapidity with which the processes act. In the latter a clear space is visible between the tops of the pipes and the cloud of fume above, the film having been exposed very quickly after the current was thrown on. Although this fume is an excellent conductor, no difficulty was had with the insulation. A potential of 63,000 volts (as calculated from transformer ratio and primary voltage) was maintained on the precipitator.

Fig. 21 shows various features of the first installation at the arsenic plant, the hot gases being treated in the three-ft. iron pipe to remove the solids, and the smaller and shorter pipe being used to precipitate a fair sample of the arsenic condensed out

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*See selected bibliography.

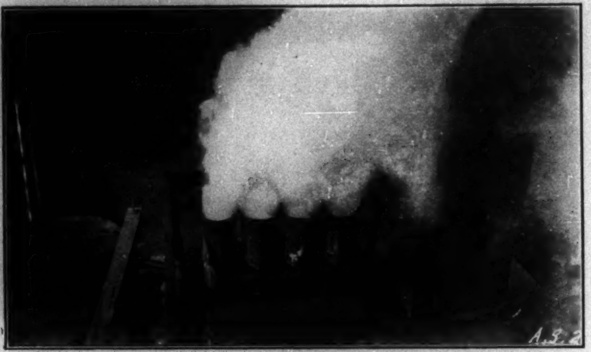

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FIG. 17—ANACONDA COPPER MINING COMPANY—TREATER AT EXPERIMENTAL LEACHING PLANT—VOLTAGE OFF

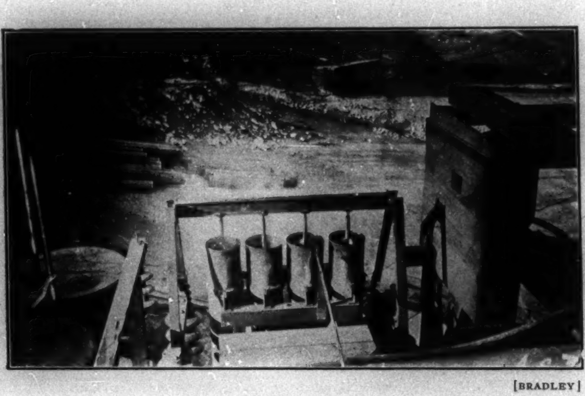

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FIG. 18—ANACONDA COPPER MINING COMPANY—TREATER AT EXPERIMENTAL LEACHING PLANT—VOLTAGE ON

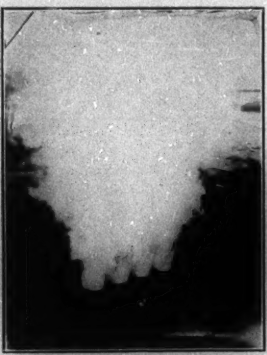

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FIG. 19—ANACONDA COPPER MINING COMPANY TEST TREATER —VOLTAGE OFF

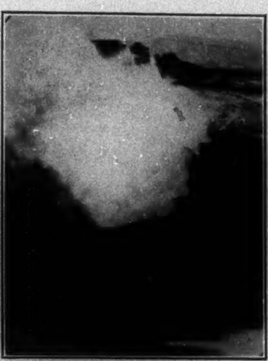

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FIG. 20 — ANACONDA COPPER MINING COMPANY TEST TREATER —IMMEDIATELY AFTER THE APPLICATION OF VOLTAGE—GOOD EXAMPLE OF THE RAPID CHANGE BETWEEN FUMES AND CLEAR GAS

[BRADLEY]

FIG. 21—EXPERIMENTAL TREATERS AT ARSENIC PLANT—ANACONDA COPPER MINING COMPANY

[BRADLEY]

FIG. 22—ELECTRICAL EQUIPMENT AT ARSENIC PLANT, ANACONDA COPPER MINING COMPANY

of the gases when cooled by admission of room air. The first test gave a precipitate in the second treater carrying 99.4 per cent arsenic trioxide. A portion of the impurity was due to volatile compounds from the wood used for fuel. Coke fuel in place of wood gave arsenic of a higher purity, sometimes reaching 99.9 As_2O_3. The electrical equipment is shown in Fig. 22.

At this point it may be interesting to review some radical differences which we have observed due to certain predetermined changes in the gases, although the precipitator and electrical apparatus were the same in all tests.

Transformer voltage low-tension	Transformer voltage high-tension (by ratio)	Watts input to transformer	Milamperes line to precipitator (d-c.)
190	26,000	100	1.0
190	26,000	180	4.0
190	26,000	740	19.0
235	32,000	930	18.0
235	32,000	1600	35.0

In neither of the above tests was the potential raised to the point of spark-over, but the following figures taken from another set of tests show plainly the difference in the amount of current which can be passed in a given precipitator and the apparent potential reached just before spark-over occurred. The only factor changed was that in the latter case the gas was slightly modified or conditioned.

Readings taken at voltage just under the sparking potential.

Voltage high-tension (by ratio)	Milamperes high-tension d-c.	
61,000	3.25	Gases unconditioned
80,000	10.5	Gases conditioned

It will thus be seen that it is difficult, if not impossible, to predict what the power consumption and voltage may be for a specified gas until actual tests have been made. The considerable variety of gas conditions already encountered has made it possible to divide gases into classes. Furthermore, methods have been developed whereby a close approximation to the required power and voltage may be obtained from the results of small-scale tests.

With a large precipitator containing many electrodes the effect of the corona load upon the transformer is different from an ordinary resistance load, in that above a certain point the current flowing through the gas between the electrodes increases more rapidly with a given rise in potential than would be the case if the electrodes were shunted by an ordinary high resistance. For these reasons it is best to employ certain potentials and electrode arrangements for certain gases, and others for gases having different characteristics. Also the mechanical handling of the collected material must be duly considered when designing a precipitator.

Other problems upon which tests have been made with the processes are mentioned below. The most recent installation was made in Worcester, Mass., at the North Works of the American Steel and Wire Company, for collecting volatilized hydrochloric acid, thus mitigating or eliminating a nuisance and preventing further damage to surrounding vegetation. No experimenting was required on this installation, thus testifying to the thoroughness with which the preliminary survey was made before designing the apparatus. The exit gases are so free from acid that it is almost impossible to detect a trace of it, even by delicate chemical methods. Table I gives the results of some tests on this installation conducted by the engineers of the American Steel and Wire Company. The precipitator is made of materials which resist corrosion.

In Cleveland, Ohio, at a sulphuric acid plant the gases come from an M. & H. kiln in which very finely divided zinc sulphides are roasted. The sulphurous gases are to be freed from the suspended particles and then delivered to a Glover tower of a lead-chamber sulphuric acid plant. The gases are to be treated at a temperature of about 800 to 1000 deg. fahr. The gases contain some free sulphuric acid, which tends to complicate the insulation problem. However, our semi-commercial tests at this plant showed that the problems could be solved, and pointed the way. Designs of several types of precipitators were prepared and at a recent conference a horizontal precipitator was decided upon and it is to be installed at once. There are to be three sections, any two of which will clean the gases, one section always being in reserve. In this problem it is necessary to conserve the sensible heat of the gases and to avoid their dilution with air, as this would materially affect the subsequent chemical operation. Mr. P. E. Landolt supervised the details of this work.

TABLE I

Cottrell Precipitator Test—North Works

Date	Water consumption		Per cent hydrochloric acid discharge water	Lb. acid per hr. precipitated.	Indicated voltage at rectifier.
	Cu. ft. per hr.	Lb.			
					volts.
1 2:30 p.m. to 3:30 p.m. Dec. 21	31.5	1969	0.455	8.959	50,000
2 4:00 p.m. to 5:00 p.m. Dec. 21	49.8	3113	0.462	14.382	62,500
3 9:50 a.m. to 10:50 a.m. Dec. 22	40.2	2513	0.113	2.840	50,000
4 10:55 a.m. to 11:55 a.m. Dec. 22	42.7	2669	0.152	4.057	62,500
5 2:45 p.m. to 3:45 p.m. Dec. 22	41.5	2594	0.138	3.580	45,000

Temp. of outside air.	Humidity	Barometer	Kw. input motor-gen.	Kw. input fan motor	Total kw. input motor-gen. and fan
deg. fahr.		inches Hg.			
1 28	66	29.2	2.24	0.90	3.14
2 31	66	29.2	2.91	0.90	3.81
3 27	69	29.4	2.24	0.90	3.14
4 28	69	29.4	2.91	0.90	3.81
5 28	69	29.3	1.57	0.90	2.47

An installation for collecting sulphuric acid mist coming from a roasting furnace is under construction for the Standard Essence Company, and since it is so similar to other sulphuric acid mist problems, no difficult features are anticipated.

At the plant of the Duquesne Reduction Company, data as to gas volumes, temperatures, draft, etc., were obtained, and tests were made with a small precipitator to show the probable amount of dust obtainable and to secure data for the design of a large installation. Contracts have been let for this installation and work is being pushed as rapidly as possible. The dust and fume from the furnaces contain tin, lead and zinc oxides. The first precipitator will contain 48 pipes 12 in. in diameter. Messrs. A. F. Meston and H. D. Egbert handled these investigations.

Similar data to those mentioned above have been obtained at a waste-metals plant of the National Lead Company. The probable recovery of values strongly warrants the immediate installation of the processes and advices to that effect have recently been received. The tests with the electrical processes were highly satisfactory, and enabled one to obtain dependable data as to the values now being lost, practically all of which can be collected readily. Mr. C. I. Weir had charge of this problem.

Owing to various reasons beyond our control, tests of the electrical processes for the cleaning of iron blast furnace gases at the Bethlehem Steel Company were delayed. Arrangements now are being pushed so as to commence tests on a fairly large scale at the earliest possible date. It should be feasible to employ the processes either for cleaning these gases for stoves and boilers, thus conserving the sensible heat contained in the gases when they come from the furnace top, or to clean them for gas engine purposes, having previously cooled them.

Arrangements have been made with the Baltimore Copper, Smelting and Rolling Company for an installation of the processes to collect sulphuric acid mist, under conditions similar to those at the Selby and Omaha plants, and also for an installation similar to that at the Raritan Copper Works for the collection of valuable fumes from the silver refinery.

At Maurer, N. J., the American Smelting and Refining Company is planning to use the processes on mixed gases from arsenic furnaces and from sintering machines. The mixed gases are apparently more easily treated at high velocities than the sintering machine gases alone. A program of tests is being carried out for the purpose of determining the best design and arrangement of the installation.

In addition to the installations and problems mentioned above, it is also of interest to note that we have under consideration the following problems, upon some of which considerable progress has been made. These include the collection of—

Aluminum oxide
Powdered starch
Powdered sugar

Powdered coal
Tin oxide for enamel
Powdered sulphur
Potash from burning of molasses
Potash from cotton seed hulls
Black smoke from round houses and other places
Fertilizer dusts
Zinc sulphides
Zinc oxides
Powdered borax
Fumes and dust from calcium carbide furnaces
Dust from rotary lime kilns
Dust from pyrite burners in sulphuric acid plants
Gold and silver from jewellers'sweepings
Fumes from linseed oil boiling kettles in varnish works
Powdered alundum
Ammonium chloride
Nitric acid, etc.

Inquiries have been received on many other problems, but the above list shows that the electrical processes are applicable to the collection of a great variety of materials, especially when it is also considered that the range of operating temperatures is from a point at least as low as 32 deg. fahr., to at least as high as 1000 deg. fahr., and at all temperatures between these two limits. Materials can be selected for each specific problem which will be suitable for the local conditions of temperature, corrosion and mechanical strength.

In addition to the use of the processes for abating a nuisance or for saving the values contained in the collected material, it is worth noting that the processes are also useful as adjuncts to other manufacturing processes or methods, either for improving operations or reducing expense. Both the lead-chamber and the contact processes of producing sulphuric acid have several places in which electrical precipitation should be valuable. Furthermore, since it is so easy to remove dust from air by these processes they may be useful in connection with the ever-present problem of suitably ventilating factories, tunnels, subways, etc.

It should be apparent that contact with such a variety of actual industrial problems as has been mentioned would furnish an impetus toward improving and simplifying precipitators and electrical apparatus, and would call forth a goodly number of patentable discoveries. While this is true, yet our policy has been not to overlook those mechanical and other operating features which would insure reliability of operation and reduce cost of installation, maintenance and operation, as well as to make the processes as nearly automatic in operation as possible. Progress along these lines is also being accompanied by efforts towards the standardization of types and sizes of precipitators and of electrical equipment, and toward adopting methods that would facilitate and expedite the collection of data, the conducting of experimental tests, and, finally, the completion of commercially and technically satisfactory installations.

The use of sphere spark gaps for the measurement of peak voltages between the discharge and collecting electrodes, and in other parts of the circuit, has led to a better understanding of some of the electric phenomena. For such measurements a convenient portable sphere spark gap, as shown in Fig. 24, has been developed. Additional data on electric phenomena have been obtained by the study of the effect, under various conditions, of especially designed inductances and resistances placed in the high-tension circuit. Methods have been devised whereby it is possible to predict quite closely the power required for the treatment of a definite quantity of a given gas. The power required for precipitation is sufficiently low so as not to be prohibitive in practically all cases where it is desirable to remove fine particles from gases. Actual power consumptions of installations now in operation will be found in the descriptions of some of the various plants already given.

Improvements have been made in rectifiers and the method of using them. Many are being operated commercially at 750 rev. per min., a speed which presents some advantages over 1800 rev. per min.

By cooperation with the manufacturers, transformer designs have been evolved which give apparatus very suitable for our work. Their reliability has been improved and the cost and time of delivery have been materially reduced. Apparatus has been developed to restore automatically normal operation after a temporary short circuit in the precipitator due to conductive precipitated material falling between the electrodes, or to similar temporary overloads resulting from other unusual conditions.

The curve shown in Fig. 25 gives the relationship between the high-tension direct current flowing into a precipitator, and the high-tension voltage impressed upon it, the latter being shown on the curve sheet as the alternating potential delivered to

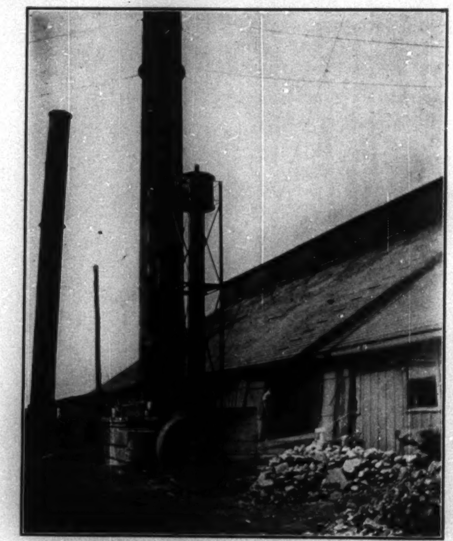

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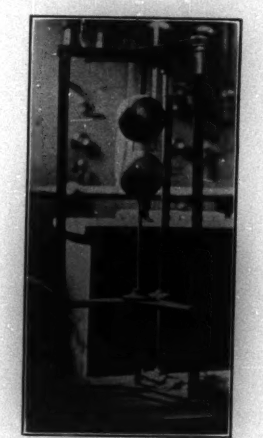
FIG. 23—TYPICAL EXPERIMENTAL TREATER INSTALLATION



[BRADLEY]

FIG. 24 — PORTABLE SPHERE SPARK GAP—RESEARCH CORPORATION DESIGN

the rectifier from the transformer and calculated from the measured low-tension voltage and the transformer ratio. Under certain conditions it would be preferable to measure the effective high-tension voltage maintained between the precipitator electrodes by means of a suitable voltmeter. In general, however, the voltage as indicated by the ratio method is sufficiently accurate for field work. The lower portion of the curve shows the uniform increase in the current with the voltage, due chiefly to insulator leakage. The upper portion of the curve shows the more rapid increase in the current as the voltage is raised above that at which corona started. The bend in this particular curve is somewhat more gradual than is usually found. This is due to a special arrangement of the electrodes whereby the corona-starting voltage varies in different parts of the precipitator.

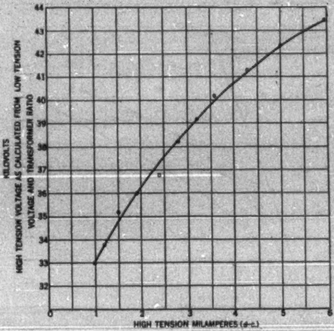


FIG. 25—CURVE SHOWING RATIO OF HIGH-TENSION VOLTAGE TO THE CURRENT CONSUMPTION—MEASUREMENT TAKEN AT PRECIPITATOR INSTALLED FOR BALBACH SMELTING AND REFINING COMPANY, NEWARK, N. J.

Fig. 26 shows the results obtained from tests made with various electrode spacings in fume-laden gases at different temperatures. Curve *A* shows the potential (measured by transformer ratio and the low-tension voltage) which, when rectified, caused a spark-over to occur between a number of parallel wires and a plate placed at varying distances from them. The wires and plates were placed in a flue through which passed zinc oxide fumes at a temperature of 600 deg. fahr. Curve *B* shows similar data obtained with the gas temperature reduced to between 350 deg. and 400 deg. fahr. Curve *C* shows similar data obtained from the same electrode system with air in the flue. The relative positions of curves *A* and *B* are what would be expected. Data are being obtained in order to plot a series of curves between corona-starting voltage (ratio method) and electrode spacings. This work has not been completed.

Fig. 27 gives in a specific case the distribution of the electrical losses in transformation, rectification and transmission of the electrical power taken from the supply lines and delivered to the precipitator. The losses of transformation are the greatest. The additional load losses of the transformer are readily calculated. The added load losses of the rectifier are not definitely known, but experience indicates that they are small in proportion to the other losses. The added load losses of the transmission line are negligible. These latter losses consist almost entirely of corona loss and insulator leakage, both of which depend upon the voltage and not upon the current. From such data it is possible to estimate very closely the capacity of apparatus required to deliver to a precipitator any given power at a certain voltage.

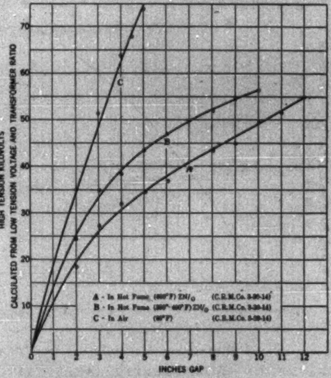


FIG. 26—CURVES SHOWING SPARKING POTENTIALS (OF RECTIFIED VOLTAGES) BETWEEN WIRES AND A PARALLEL PLATE, FOR VARIOUS GAP SPACINGS

Valuable knowledge has been gained of friction loss of gases passing through precipitators, and through inlet and outlet passages, and of how to get uniform gas distribution. The latter is more difficult to control when the velocity of the gas is low than when it is high.

Valuable experience has also been gained in the field of measuring and sampling large volumes of moving gases, and methods suitable for our work have been evolved which have been proved of practical reliability by results on large-scale installations. Several complex flue systems and stacks have been explored and data obtained in such a manner that reliable predictions were possible, as to the effect of the installation of the electrical precipitation equipment. In many cases this is a very pertinent question, especially when natural draft is depended upon to move the gases.

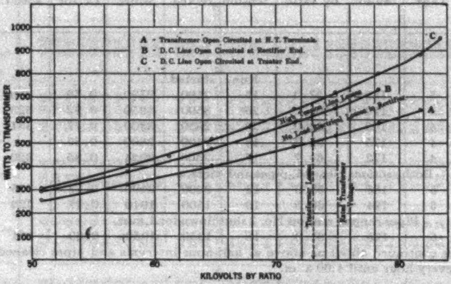


FIG. 27—POWER LOSS DATA

Transformer 7½ kv-a., 75,000 volts, 60 ~. Rectifier type—2 arm—8 shoe—steel shaft. Line insulators 2 per line trans. to rect., 11 in d-c. line.

The log sheet shown in Table II gives a typical set of readings taken during a run on a two-section precipitator. Each section consists of twenty 12-in. diameter pipes, 12 ft. long. The log sheet shows a considerable variation in the power consumption and in power factor. This was one of the first test runs made in the application of the electrical precipitation processes to a new problem. Causes for each unsteady or unfavorable condition are sought and the effect of each on the percentage of precipitation is noted and steps are taken toward their elimination. Finally, with the proper conditions secured, the operation becomes steady and automatic. Electrical data and gas measurements are taken simultaneously.

A typical field data sheet is given in Table III. It was used in connection with flue loss determinations, and is a copy of actual test data obtained in a 24-hour test. (See Fig. 28 for arrangement). From left to right the columns shown give the following information:

TABLE II

EXPERIMENTAL DATA ON TWO PRECIPITATOR SECTIONS OF TWENTY 12-IN. DIAM. PIPES EACH. SINGLE WIRE ELECTRODE

Time	Tap*	Volts low-tension	Kilo-volts high-tension by ratio	Amps. low-tension	Watts corrected	Volt-amps.	Power factor	Fan speed.	Difference in static Fan inlet & outlet in oz .per sq. in.
P.M.									
4:30				Run	started.				
5:00	5	182	57.0	15	2100	2730	0.76	330	1¼
5:30	4	170	64.0	25	3500	4250	0.82	323	1¼
6:00	4	165	62.0	20	2550	3300	0.77	331	1¼†
6:30	4	175	65.7	16	2400	2800	0.85	...	....
7:00	4	172	64.7	17	2500	2924	0.85	320	1
8:40	Both sections cleaned, pipes and wires.								
8:45	5	185	58.0	13	2000	2400	0.83	325	1¼
9:15	5	194	60.5	10	1500	1940	0.77	320	1
9:40	Pipes rapped section No. 2 shut down for 1 min.								
9:45	5	195	61.0	10	1350	1950	0.69	301	1
Readings continued about as above at half-hour intervals and pipes cleaned by hammering every hour until 4:00 a. m.									
A.M.									
4:00	5	195	61.0	10	1350	1950	0.69	285	½
4:25		Pipes	rapped.						
4:30	5	200	62.5	8	1150	1600	0.72	292	⅞‡
5:00	5	200	62.5	8	1250	1600	0.78	268	⅞
5:35	5	200	62.5	12	1800	2400	0.75	270	¾
6:00	5	205	64.0	8	1200	1640	0.73	277	¾
6:30	5	200	62.5	6	1000	1200	0.83	270	⅞
7:00	5	197	61.5	6	1050	1180	0.89	276	⅞
7:30	5	200	62.5	9	1150	1800	0.64	273	⅞
8:20	5	202	63.0	8	1000	1620	0.62	278	⅞
8:30		Run dis	continued						

* Transformer ratio tap 4—200 to 75,000 volts.
" " " 5—200 to 62,500 "

† Pipes rapped

‡ Pipes rapped at 5:20

Column 1. Gage zero—on the differential gage used; a zero reading was always taken.

TABLE III

Research Corporation

Typical Field Data Sheet

For Sampling Tests Using Electric Precipitator

July 22-23, 1914

Gage zero	Stack reading 1	V. H. in. H_2O stack 1	Sampler reading 2	V. H. in. H_2O sampler 2	Temp. of stack 1-2	Temp. of precipitator	Stack vel. ft./sec. 1	Precipitator 6-in. pipe vel. ft./sec. 2	Stack vol. cu. ft. per min. 1	Precipitator vol. cu. ft. per min. 2	Std. vol. stack. 1	Std. vol. precipitator 2	Per cent handled $\frac{2}{1}$	Time out.	Time.
															Start.
0.045	0.330	0.142	0.330	0.142	780	380	38.6	38.6	53,200	463			0.870	3:30p. m.	3:00 p.m.
0.045	0.360	0.157	0.350	0.152	780	450	40.6	39.9	56,000	479			0.856		4:00
0.040	0.430	0.195	0.410	0.185	815	450	46.0	44.7	63,500	536			0.844		4:30
	0.400	0.190	0.410	0.185	760	465	44.2	43.6	61,000	523			0.857		5:00
	0.300	0.130	0.310	0.135	760	500	36.6	37.3	50,500	448			0.886		5:30
	0.310	0.135	0.300	0.130	805	465	38.0	37.3	52,400	448			0.856		6:00
	0.280	0.120	0.290	0.125	670	380	33.8	34.5	46,600	414			0.888		6:30
	0.200	0.080	0.190	0.075	760	350	28.7	27.8	39,600	334			0.843		7:00
	0.200	0.080	0.220	0.090	800	385	28.7	30.4	39,600	365			0.922		7:30
0.040	0.190	0.075	0.180	0.070	780	270	28.1	27.2	38,800	326			0.842		8:00
0.040															8:30
0.045	0.200	0.077	0.420	0.187	800	320	28.8	44.6	39,700	535			1.350		9:00
0.050	0.220	0.085	0.230	0.090	770	270	29.7	30.6	41,300	367			0.887		9:30
0.050	0.220	0.085	0.230	0.090	750	260	29.4	30.3	40,600	364			0.897		10:00
0.055			10-11	P.M.	6" line pl	ugged wi	th water	drain plu	gged—no	gage re	ading.				10:30
0.050	0.170	0.060	0.290	0.120	490	180	21.9	31.0	30,200	372			1.225		11:30
0.050	0.170	0.060	0.240	0.095	470	170	21.7	27.3	30,000	328			1.095		12:00 m.n.
0.055	0.420	0.182	0.410	0.177	700	220	42.3	41.7	57,000	500			0.876		12:30 a.m.
0.050	0.460	0.205	0.500	0.225	690	440	44.5	46.5	61,400	570			0.927		1:00
	0.440	0.195	0.430	0.190	860	370	46.7	46.0	64,500	552			0.858		1:30
	0.420	0.185	0.430	0.190	840	400	45.3	46.0	62,500	552			0.883		2:00
	0.390	0.170	0.410	0.180	850	380	43.3	44.6	59,700	535			0.894		2:30
	0.350	0.150	0.350	0.150	840	350	40.5	40.5	55,900	486			0.869		3:00
	0.240	0.095	0.240	0.095	860	270	32.6	32.6	45,000	391			0.869		3:30
	0.280	0.115	0.260	0.105	900	330	36.3	34.7	50,100	435			0.869		4:00
	0.410	0.180	0.450	0.200	850	320	44.6	47.1	61,500	535			0.869		4:30
	0.450	0.200	0.420	0.185	830	340	46.7	44.8	64,500	538			0.836		5:00
	0.480	0.215	0.390	0.170	860	340	49.0	43.5	67,600	522			0.772		5:30
	0.470	0.210	0.460	0.250	830	360	47.8	47.3	66,000	527			0.796		6:00
	0.420	0.185	0.400	0.175	820	340	44.7	43.4	61,600	521			0.842		6:30
	0.480	0.215	0.480	0.215	770	360	47.2	47.2	65,100	506			0.776		7:00
	0.420	0.185	0.420	0.185	720	320	42.9	42.9	59,200	514			0.867		7:30
0.050	0.410	0.180	0.410	0.180	710	320	42.2	42.2	58,200	506			0.867		8:00
0.045	0.360	0.157	0.355	0.150	685	300	39.1	38.1	54,000	457			0.846		8:30
0.050	0.400	0.175	0.400	0.175	780	280	44.0	44.0	60,700	528			0.868		9:00
0.050	0.420	0.185	0.400	0.175	700	340	42.6	41.4	58,800	497			0.845		9:30
															10:00
0.040	0.440	0.200	0.425	0.192	860	420	47.3	46.3	65,300	556			0.847	10:10-10:50	11:00
0.045	0.425	0.190	0.420	0.187	915	520	47.0	46.7	64,900	570			0.873		11:30
0.040	0.460	0.210	0.450	0.205	910	505	49.3	48.8	68,000	586			0.862		12:00 m.
													32830		

Note: Readings taken and samples drawn 60 ft. above base of stack. Stack 160 ft. in height.

Column 2. Stack reading—a differential gage reading, indicating the gas velocities in the stack. The gage is connected to a pitot tube in a 6-inch diam. "companion" pipe shown in Fig. 28.

" 3. V.H. in. H_2O stack—is the gas velocity head in inches H_2O in the stack and is one-half the difference between columns 1 and 2. (Gage factor = 0.5)

" 4. Sampler reading—is the reading indicated on the differential gage, connected to the pitot tube in the 6-in. diam. sampler pipe. (See Fig. 28).

" 5. V.H. in. H_2O sampler—is the gas velocity head in inches H_2O in the 6-inch diam. sampler pipe. (Gage factor = 0.5).

" 6. Temperature of stack gases in degrees fahrenheit.

" 7. " " gases in precipitator in deg. fahrenheit.

" 8. Stack vel. ft. per sec.—velocity of gases in stack.

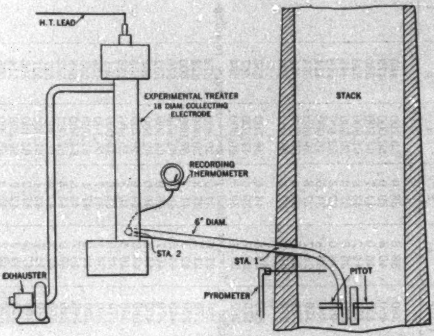


FIG. 28

Column 9. Precipitator 6-inch pipe vel. ft. per sec.—velocity of gases in 6-in. diam. sampler pipe to precipitator.

" 10. Stack vol. cu. ft. per min.—volume of stack gases per minute.

" 11. Precipitator vol. cu. ft. per min.—volume of precipitator gases per minute.

" 12. Std. vol. stack—volume of stack gases at 32 deg. fahr., 29.92 in. Hg.

" 13. Std. Precipitator vol.—Volume of precipitator gases at 32 deg. fahr., 29.92 in. Hg.

" 14. Per cent handled—ratio of gases handled in precipitator to total gases in stack.

" 15. Time out—record of shut-downs or troubles incidental to the test.

" 16. Time—schedule of readings taken during test.

In connection with the above data, sets of daily measurements were made of the quantities and conditions of the gases in the stack. The details of these figures are given in the form of curve sheets as Figs. 29, 30, 31, and 32. These results are summarized in Table IV.

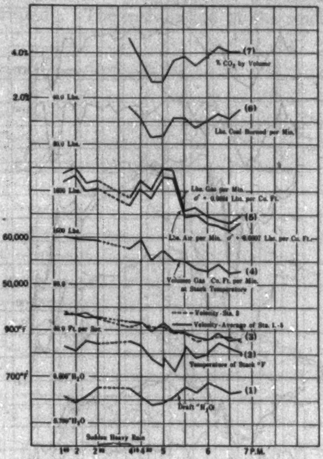


FIG. 29

Weather generally fair—Barometer 29.47 in. Hg.
Elevation of station 440 + 65 = 505 ft. A. S. L.
Barometer correction for velocity:
V from chart × 1.008 = V actual.
Correction for carbon dioxide:
V from chart × 0.990 = V actual (4 per cent CO_2)

Average Results.

Draft : 0.72 in H_2O
Stack temperature: 808 deg. fahr.
Air temperature : 75 " "
Gas velocity : 40.5 ft. per sec.
Gas velocity (3) : 40.6 ft. per sec.
Gas velocity : 2430 ft. per min.
Gas velocity : 27.2 mi. per hr.
Gas volume : 55,900 cu. ft. per min.

Gas weight : 1745 lb. per min. (air)
" weight : 1780 lb. per min. (gas)
Standard volume : 21,600 cu. ft. per min.
CO_2% by volume : 3.67 per cent.
Lb. carbon: 26.6 burned per min.
Lb. coal : 30.6 burned per min.

Scale

Horizontal:
1 division = 1 hour
Vertical :
0.1 division = 0.02 in. H_2O draft. (1)
= 20 deg. fahr. stack temp. (2)
= 1.0 ft. per sec. (3)
= 1000 cu. ft. per min. (4)
= 20.0 lb. per min. gas (5)
= 0.2 per cent CO_2 (7)
= 2 lb. coal (6)

Temperature records kept during the above-mentioned test are given as Figs. 33 and 34.

In Fig. 35 a sketch of the electric precipitator used for the demonstration in connection with this paper is shown. This sketch includes the method of showing corona effects and the method of producing fume and dust for precipitation, in connection with the experiments prepared for this demonstration.

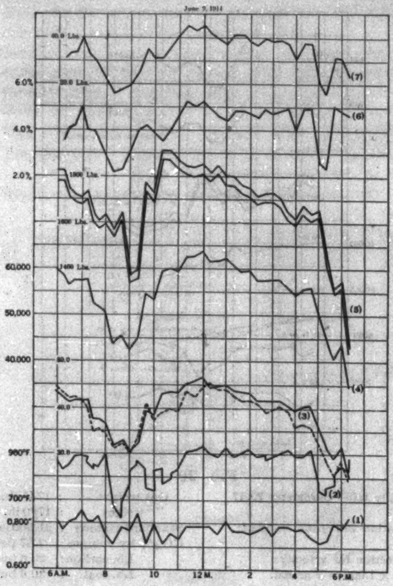


FIG. 30

Scale

Abscissa: 1 division = 2 hours

Ordinate:

(1) 0.1 division = 0.02 in. H_2O draft
(2) = 20 deg. fahr. stack temp.
(3) = 1.0 ft. per sec. gas velocity
(4) = 1000 cu. ft. per min. gas volume
(5) = 20 lb. per min. gas weight
(6) = 0.2 per cent CO_2 by vol.
(7) = 20 lb. per min. coal burned.

Several additional installations of these processes have been made under the direction of Mr. Walter A. Schmidt, of Los

Angeles, California, at various locations in the Pacific Coast States, Canada and Germany. The one which treats the largest volume of gases is at the plant of the Riverside Portland Cement Company. The installation at the smelter near Trail, B. C., treats about 100,000 cu. ft. of gases per minute coming from lead blast furnaces. A precipitator has been installed for handling the gases from one 1000-barrel cement kiln at Buffington, Indiana, and a continuous thirty-day test showed an aver-

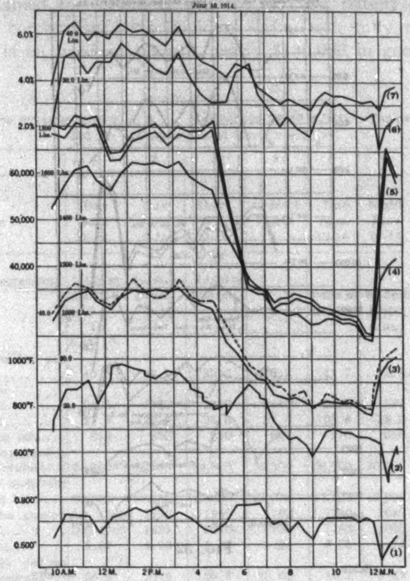


FIG. 31

Scale

Abscissa: 1 division = 2 hours

Ordinate:

(1) 0.1 division = 0.02 in. H_2O draft
(2) = 20 deg. fahr. stack temp.
(3) = 1.0 ft. per sec. gas velocity
(4) = 1000 cu. ft. per min. gas volume
(5) = 20 lb. per min. gas weight
(6) = 0.2 per cent CO_2 by vol.
(7) = 20 lb. per min coal burned.

age of approximately 95 per cent of the dust removed from between 60,000 and 75,000 cu. ft. of gas per minute. The temperature of the gases in this case reached 750 deg. cent.

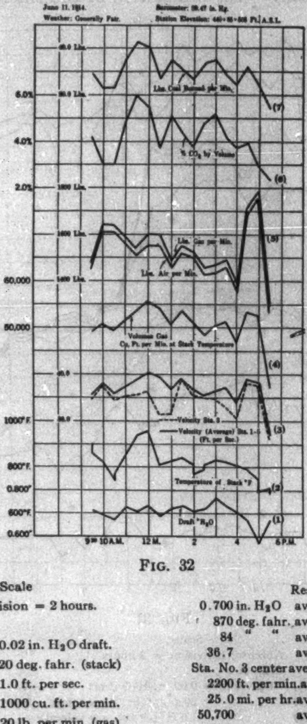


FIG. 32

Scale

Abscissa: 1 division = 2 hours.
Ordinate:
(1) 0.1 division = 0.02 in. H_2O draft.
(2) = 20 deg. fahr. (stack)
(3) = 1.0 ft. per sec.
(4) = 1000 cu. ft. per min.
(5) = 20 lb. per min. (gas)
(6) = 0.2 per cent CO_2
(7) = 2 lb. coal per min.

Results

0.700 in. H_2O	average draft
870 deg. fahr.	average stack temp.
84 " "	average air temp.
36.7	average gas velocity
Sta. No. 3 center	average gas velocity 34.4
2200 ft. per min.	average gas velocity.
25.0 mi. per hr.	average gas velocity.
50,700	average gas volume
1520	average gas wt. (air)
1550	average gas wt. (gas)
18,800	average std. volume
4.17	average % CO_2 by volume
26.2	average lb. carbon
30.1	average lb. coal

In conclusion it is to be stated that the past three years have seen the electrical processes (Cottrell patents) in constantly growing use and demand, several commercial installations having produced excellent results, and the future is full of promise. The corporation has definitely established itself commercially in the short time intervening since its organization. The total capital paid into the treasury was $10,100. From the receipts so far obtained for technical services and for patent rights, all of the corporation's stockholders have been fully repaid, and there is on hand at present nearly $150,000 in good and negotiable securities as a net surplus, with only ordinary current accounts owing. Further income as royalties from installations now in operation, under way, or contracted for, will materially increase the above amount, so that a fund for further sceintific research has already been created, and this directly from the industries benefited by the processes administered by the corporation.

TABLE IV

ELEVATION OF STATION 505 FT. A. S. L. BAROMETER 29.47 IN. HG. TOP OF STACK —505 FT. A. S. L. STACK HEIGHT—160 FT.

	1	2	3	4	5	6	7
Date	Day June 8-14	Day June 9-14	Day June 9-14	Average 2 & 3	Day June 10-14	Night June 10-14	Day June 11-14
Period of measurement.	1:45p.m. to2:30 " 4:15 " to 6:45 "	6 a.m. to 12 m.	12:20 to 6:20 pm.		9:45A.m 5:45pm.	6:45pm 12:40 a. m.	.9:30am 5:30pm
Velocity of gas feet per sec.	40.5	42.1	39.3	40.7	41.7	21.7	36.7
Velocity of gas. Feet/minute	2430	2520	2360	2440	2520	1320	2220
Miles/hour	27.2	28.6	26.6	27.6	28.6	15.0	25.2
Flue temp. deg. fahr.	810	830	880	855	870	690	870
Volume of gascu. ft/min. @ flue temperature	55,900	58,100	54,300	56,200	58,000	30,200	51,000
Volume of gas. cu. ft/min at 29.92" Hg. 32° F.	21,600	22,150	19,900	21,050	21,450	12,900	18,900
Weight of gas passing lb./min.	Air 1745 Gas 1780	1790 1825	1610 1640	1700 1735	1730 1765	1040 1060	1525 1555
% CO_2 by vol.	3.67	4.00	4.47	4.24	4.36	2.12	4.17
Calculated lb. carbon burned per minute	26.6	29.6	29.7	29.65	31.3	9.12	26.2
Calculated lb. coal burned per minute	30.6	34.1	34.2	34.15	36.0	10.5	30.4
Stack draft inches H_2O.	0.720	0.781	0.775	0.778	0.712	0.692	0.700
Sets of fires	1-8	1-8	1-8	1-8	1-8	1-4	1-7
No. of fires	88	88	88	88	88	48	78
Air temp. deg. fahr	75	61	67	64	80	77	84

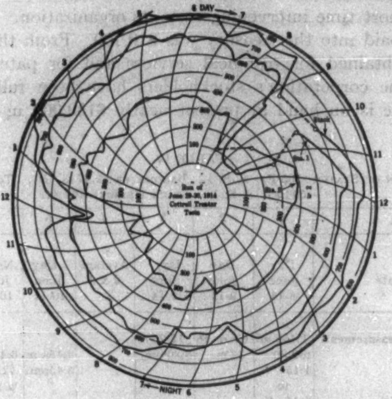


FIG. 33—TEMPERATURE RECORDS IN CONNECTION WITH ELECTRIC PRECIPITATOR TESTS

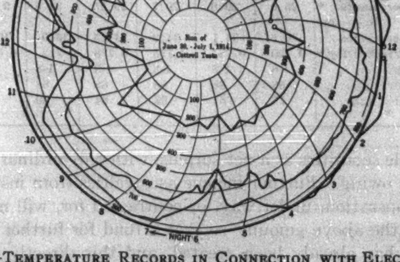


FIG. 34—TEMPERATURE RECORDS IN CONNECTION WITH ELECTRIC PRECIPITATOR TESTS

Messrs. H. D. Egbert, P. E. Landolt, A. F. Meston, C. I. Weir, J. C. Hale, H. A. Burns and H. M. Pier, assistant engineers in the employ of the corporation, have rendered very valuable service in connection with the various problems which have been encountered and have materially aided in overcoming the many difficulties. They have been very loyal and devoted to the cause, working in the main under very unfavorable conditions and receiving smaller compensation during most of the three years the corporation has been operating than they could have obtained elsewhere, and they are to be complimented and thanked for their zealous and efficient service. The technical men in the various plants have likewise taken a keen interest in the work and have rendered valuable services and have been of great assistance in enabling the presentation of a report of such progress, and thanks are due them.

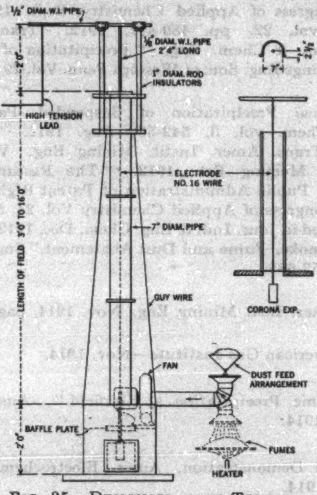

1/2" DIAM. W.I. PIPE
1/2" DIAM. W.I. PIPE 2'4" LONG
1" DIAM. ROD INSULATORS
2'0"
HIGH TENSION LEAD
7"
2 1/2"
ELECTRODE NO. 16 WIRE
LENGTH OF FIELD 3'0" TO 16'0"
7" DIAM. PIPE
GUY WIRE
CORONA EXP.
FAN
DUST FEED ARRANGEMENT
BAFFLE PLATE
2'0"
FUMES
HEATER

FIG. 35—DEMONSTRATION TREATER

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W. S. Franklin: Let me ask Mr. Bradley how to get rid of the material which accumulates in the pipes.

Linn Bradley: This is a matter which presented some difficulty. If it is a liquid it will run off, and if it is a mixture of liquid and solid, it will not run off unless it is of proper consistency. If you have a dry dust it is easy enough to shake it off. You have to design your plant to suit the problem. Fumes that are all dry can be handled in about the same way; that is, if they are of the same physical character. If they are of a granular character, they must be operated in a different way from fumes which are of a fine formation.

Saul Dushman: In order to obtain high-voltage rectified current for use in precipitation of smoke and dust, it has hitherto been customary to use a mechanical rectifier. Very recently it has been found possible to produce a much simpler form of rectifier which does not necessitate any moving parts. This type of rectifier (which has been designated the "kenotron") operates with a pure electron discharge produced in a highly evacuated tube from an incandescent filament, and is based upon the theoretical investigations of Dr. Langmuir on the laws of electron emission from incandescent bodies in high vacua. The current can pass through such a tube only in that direction which makes the filament cathode, and the tube, therefore, acts as a perfect rectifier. Rectifiers of this type may be constructed to operate at the highest voltages used in commercial practise and at an efficiency which is well over 95 per cent, while the currents that can be rectified are of the order of magnitude of 0.1 to 0.5 ampere. Owing to the fact that the kenotron possesses positive characteristics, any number of them can be operated in parallel, in series with a resistance, and each kenotron merely carries its proper share of the total current.

All the auxiliary apparatus required to operate this rectifier is a storage battery or transformer for lighting the filament. The maximum current that can be rectified by any given kenotron depends only upon the temperature of the cathode, and by regulating the temperature of the latter, it is therefore possible to obtain perfect control over the current through the load.

A complete description of the device will be published soon; but these remarks will probably serve to show that a rectifier constructed on the above principles ought to find a useful field of application in the work on precipitation of smoke and dust.

W. S. Franklin: Mr. Bradley has mentioned some difficulties from occasional sparking and arc formation. It seems to me that it might be a help to connect a considerable inductance between the rectifier and precipitator or treater, and then connect a condenser between the precipitator and the ground.

Halbert P. Hill: What is the result of commutated wave lengths, what improvement is found in this apparatus; in other words, the first switches were 10 per cent of the wave, but as commutated they have gone up to greater length—is there greater efficiency by commutating the wave?

W. S. Franklin: I do not believe that the possibilities of the influence type of electric machine have been determined, and I do believe that the field for electro-deposition of fumes is so enormously wide that the time will come, and come very soon, when the two or three watts of high-voltage power that can be delivered by an influence machine will be extremely important. The influence machine is, no doubt, the simplest type of high-voltage source you can have for a small installation, and it is important to determine what the possibilities of the influence machine are.

A. F. Nesbit: Mr. Strong and I personally tried out the type of rectifier which has been referred to, in this 1000-cu. ft. outfit, and we find it is practically as good as the Lempe rectifier. We have taken oscillograms of its action; and I see no reason why the suggestion is not eminently fitting at this time.

L. W. Chubb: I would like to ask the authors whether the different kinds of fumes require a different voltage on the wire, and what range of intensity of field is required for the different kinds of fumes. In the first articles which I read on this subject I remember the flues were very much smaller. Mr. Bradley speaks today of flues four or five feet in diameter, which seems to be a step in the wrong direction, because to get the same intensity at the wires requires much higher voltage to be rectified.

John B. Taylor: Where is the definite dividing line between plain mechanical action and action that depends on ionization? The results set forth in these papers could be readily understood on the theory of attraction and repulsion, without going into the ionic theory. Are there any experiments that can be cited to show that the precipitation will not take place until the voltage is brought above a point where corona starts? If it is an ionization action, distinct from a plain mechanical attraction and repulsion, there should seem to be a fairly definite voltage at which the clearing up will begin and below which it will not.

W. S. Franklin: Let us consider a polarized particle, either in a magnetic field, where it is a north pole on one side and a south pole on the other, or in an electric field, where it becomes positively charged on one side and negatively on the other. Such a particle requires a field of varying intensity to be acted on by any mechanical force at all, and the magnitude of the force decreases at an enormous rate as the size of the particles decreases. It seems to me as almost certain that you never could get an electric field strong enough and varying rapidly enough to exert a perceptible force on a polarized particle, of the size of smoke or fume particles. Such a small particle must have an actual excess of positive or negative charge to be acted upon by a perceptible force. It is only in the case of large particles, such as pieces of paper, that a mere polarization leads to a percpetible force action in an electric field.

J. H. Davis: I ask the authors if they intend to develop their process so that it will be applicable to steam locomotives.

W. W. Strong: I beg to differ from Prof. Franklin concerning his enthusiasm about the influence machine. At the present time a small transformer, weighing fifty or sixty pounds, is being made to operate with alternating current, giving 30 or 40 thousand volts, and can be used in connection with Mr. Dushman's rectifier. It is a very satisfactory instrument, and I think will serve to precipitate quite large volumes of fumes, smoke fumes and the fumes emitted by ordinary locomotives, especially when being fired. As to the precipitation of fumes emitted by locomotives, one trouble you would have at present is that the ordinary generators used for lighting in trains are almost entirely direct-current generators, and it would be necessary to replace them with alternating-current generators, in order to apply this system to the precipitation of smoke from locomotives. Then it must also be remembered that electrical precipitation can not be used to treat gases flowing at a high speed. Electrical precipitation is being applied to the problem of collecting the smoke from locomotives while the fires are being started.

As to precipitation by means of polarization, that is impracticable altogether, in fact you do not get very good precipitation at all until you get almost a maximum corona current between your electrodes; that is, the precipitation becomes better and better as you approach the sparking distance. That is where the maximum ionization current of the curve flows. According to the work of Milliken and others, it is quite probable that these little particles receive a charge of fifty to one hundred times the charge of the ordinary electrode.

Linn Bradley: One of the questions asked by Mr. Hill, in connection with the length of the shoe, is one of the matters which I will take up first. We find that with a given transformer and a given sized precipitating device, and with the transformer operated from a small alternator, it is quite essential that we have a long arc of contact, so-called, on our rectifier. If we have a point to point contact, it is difficult to get enough energy into a large precipitator to produce a sufficiently high rate of ionization. The frequency of the power supply circuit in some cases has some effect. It is a good plan to have the arc of contact a certain length (and this is best determined in practise), for where there is a large current flowing into the precipitator without the proper arc of contact, there are liable to be rather violent surges. This condition is detrimental and, in fact, has at times seemed to hinder precipitation.

As to Prof. Franklin's remarks regarding the insertion of inductance in the high-tension d-c. circuit, this has been done and we have found that at times it is an improvement. We have placed inductance in this part of the circuit and tests have indicated that the high-frequency surges were of such character as to give a potential drop of 20,000 to 25,000 volts between the terminals of the special choke coil. We have found in some cases that the use of inductance of this kind makes it possible to maintain a higher effective voltage in the precipitator than without it.

As to the point which Mr. Chubb raised, in connection with the intensity of ionization and the diameter of the collecting pipe, in my opinion there is a preferred design of precipitator for any given gas problem. The precipitator pipes should not be of too great a diameter nor of too small a diameter. I believe that the practical considerations of a fume collection problem are of greater importance than some of the theoretical questions. The increase in energy due to large diameter pipes that is consumed in precipitating particles, in the majority of cases we have had so far, has been so small as to be of no great importance. What the plant operators require is precipitation of their fume or dust. They care but little concerning how you do it. The practical solution of their problem has interested them much more than a possible decrease in energy consumption. Experiments with a 4 ft. diameter pipe certainly showed that its use was feasible and practicable, and, yet, while I would not for practical reasons recommend at present the universal use of such potentials as 200,000 or 250,000 volts, nevertheless, these potentials do operate very satisfactorily under suitable conditions.

We have also found that if there is not a sufficient potential in the precipitator, proper precipitation of the fume and dust is not obtained. The precipitation apparatus is so designed as to give sufficient flexibility to reach the proper field intensity and to insure the most economical installation, practicability being of primary importance.

There is another point which may be mentioned in connection with power consumption and which, perhaps, may seem to be somewhat contradictory to what Dr. Strong said. We have found that it is possible to have too great a potential for most economical operation. Particles of dust have been precipitated and then de-precipitated or blown off the electrodes by increasing the potential.

W. S. Franklin: Does the odor disappear with the smoke?

Linn Bradley: I have never tested coal smoke for elimination of odor. I think that the results would largely depend on the character of the smoke. If the volatile constituents are completely removed, probably the odor would disappear. Carbon is not volatile at ordinary temperatures, so if the smoke consisted entirely of carbon particles there would be no odor. However, there probably would be volatile compounds, such as sulphur dioxide, present, which would give an odor. True gases, obviously, are not directly removed.

W. S. Franklin: I think Mr. Bradley does not appreciate the absolute necessity of a grounded condenser back of the choke coil, to give any efficacy whatever to the elimination of surges by such choke coil. I mean in capacity. Whether the *Y* line is enough, I do not know. I do not think a small *Y* line would have enough capacity to make a choke coil effective in that respect. If he connects a condenser to the ground back of the choke coil, it will increase the capacity.

Linn Bradley: The precipitator acts as a grounded condenser. If it is large enough it should answer your purpose and it would be the simplest type of condenser available for practical operation. In practise we do have irregularities in the precipitator. To a certain extent, these irregularities do not interfere, so we make no extra effort to overcome them.

If the conditions are such that sparks grow into current arcs, then there should be some apparatus for overcoming or breaking these current arcs and making the operation automatic and stable. The character of the circuit and service is such as to promote surges. The magnitude and frequency of the surges probably vary. If they can be reflected, kept out of the precipitating device, and then dissipated, the actual amount of energy in them being quite small it would probably be desirable.

S. M. Kintner (communicated after adjournment): Dr. Franklin lays special emphasis on the use of a condenser as a means of limiting the voltage surges on the precipitators. This calls to mind a series of tests that I made several years ago, on "static interrupters." These interrupters were placed in circuit with the high-tension side of power transmission transformers and were employed as a means of limiting the voltage strains between turns on the end coils of the transformers. The "static interrupter" consisted of an air-core choke coil which was placed in series with the line, and of a condenser, which was connected between the line and ground, the condenser connection to the line being made between the transformer that it was desired to protect, and the choke coil.

A series of tests, in which a special transformer of about 200 kw. was employed, revealed the fact that of the protection afforded the transformer by the "static interrupter," about 90 per cent of it was due to the choke coil. As the choke coil, alone, could be built for about one-third of the cost of the complete "static interrupter," it was decided to discontinue the use of the latter.

The apparatus under discussion appears to me to be of the same general type and if different at all, it is in a way to make it still less favorable to the use of a condenser. The precipitator is itself a condenser and the protection of a condenser by the use of another condenser, in shunt to it, does not appear to me to be good practise.

H. P. Hill (communicated after adjournment): From repeated tests I have made in my laboratory I find that with any make-and-break type of rectifying switch—similar to the Lempe—in which the current arcs from the rotor arm to the contact shoe, this arcing sets up the high-frequency surge. This in turn decreases the capacity of the treater, from the fact that the substance tested takes a charge and a potential discharge while passing through each cycle. The ideal method of course would be to use a static machine for this service.

The next best thing is to use a positive contact rectifying switch and commutate all of the wave. By this method nearly true direct current is furnished the treater and the capacity is greatly increased over a unidirectional current, or a treater in which only part of the wave is utilized. In the slides shown in Prof. Nesbit's paper this charging and discharging of the fine tissue paper, as shown and described by him, is due to rectifying only the apex of the wave and the treater discharges itself before the next wave is rectified.

It has been proved conclusively that high-frequency surges are set up between the treater and rectifier and various methods have been used to protect the transformer and to reduce this surging, including air-cooled impedance coils. From the result of my experiments a positive contact switch is the only logical thing to use, as it eliminates all surges, takes a great strain off the transformer and provides a uniform flow of current on the treater.

None of the papers seems to give any data as to the result of various frequencies. In my experiments I have used rectifying switches with shoes commutating 10 per cent of the wave, up to as high as 70 per cent of the wave, and the more of the wave you can commutate the more effective the treater.

In Prof. Strong's paper he gives Stokes's law and discusses it at considerable length, but I cannot see how this law would apply unless the current was always a known quantity, or, in other words, direct current. If the kilovolt-amperes for a given quantity were based on true direct current this would vary in proportion to the amount of the wave that was commutated during the element of time. I have used this apparatus in various substances, at various voltages with several types of treaters and obtained better results with 60 cycles than with 25 cycles, and still better results with a positive contact switch, and the more of the wave that was commutated the less milliamperes on the treater were required; besides, with a positive contact switch the deteriorating effects on the end coils of the transformer due to corona were almost entirely eliminated.

I have conducted some experiments with electrolytic rectifiers consisting of 400 aluminum saucers with tin plates in the center, separated with glass separators, and each saucer filled with a bicarbonate of soda solution and the whole rectifier encased in a glass tube, the idea being to eliminate the mechanical rectifying switch, and while good results were obtained, only one side of the wave was commutated and the cost of the apparatus was prohibitive and very uncertain. I also operated a test with some large mercury valve tubes. As the result of my investigation I finally decided that a positive contact switch commutating the entire wave was the most practical and most efficient device.

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ELECTRICAL PORCELAIN

I. TESTING WITH A HIGH-FREQUENCY OSCILLATOR. II. THE PROBLEMATICAL POINTS OF MANUFACTURE. III. EXPERIENCES AND EXPERIMENTAL INVESTIGATIONS

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

Part I treats of the reasons for using the high-frequency oscillator for testing porcelain insulators. The oscillator is a combination of a 60-cycle transformer, a condenser, a spark gap, and an oscillation or coreless transformer. The 60-cycle potential charges the condenser and the condenser discharges through the gap and the coreless transformer. This sets up high-frequency wave trains of the same nature as the wave trains that take place on the transmission line. This high-frequency potential strain is the only kind that damages the insulators. The 60-cycle potential is always far below the puncture potential and arc-over potential of the insulators.

In Part II it is shown that the principal factors in the manufacture of porcelain which affect the final product are:

1. The choice of ingredients—ball clay, china clay, feldspar, and flint.
2. The problem involved in getting a homogeneous mixture of these pulverized materials.
3. The problem of drying out the moisture without causing unequal contractions which crack the green porcelain.
4. The early dehydration in the furnace, in which as much as 14 per cent of moisture is given out.
5. Proper time and temperature for vitrification.

The mechanical processes through which porcelain is carried are of the greatest importance in getting good electrical porcelain. It can be stated that defective porcelains are in general due to the accidents of manufacture, the dielectric strength of all the porcelains being passably good except for flaws.

Part III includes data on tests carried out mostly with the high-frequency outfit. An electrical method is shown of producing failure along invisible cleavage surfaces in the porcelain body. This examination should be useful to the porcelain manufacturer to indicate how nearly the porcelain is approaching to a weakness which will cause the rejection of the porcelain piece. Another method, using potential gradient to investigate the homogeneity of the porcelain, may be found of use in determining the efficiency of the pug mill which is used to mix the ingredients when the porcelain is in the early plastic stage.

1. OBJECT OF THE PAPER

IN PREPARING this paper there has been in view a number of objects. The many electrical and ceramic problems encountered are complex and widely ramified. There are several of these problems which have only been mentioned. There are ceramic problems on which definite information has not yet been found. There are methods of examination of porcelain which are still in the stages of development. The experiments given are definite so far as they go, but more experience is necessary to crystallize the methods into permanent forms. There is one main object which it is hoped to accomplish: namely, to call attention to the use of the high-frequency oscillator as a rational method of testing insulators.

Some of the subjects treated are listed below:

(a) A brief analysis of the general problem of continuity of service on transmission lines in which porcelain insulators assume a primary and important position.

(b) An analysis of the electrical strains which are actually imposed on insulators in practise.

(c) A description of the high-frequency oscillator which has been designed to reproduce the electrical strains imposed on the insulators.

(d) A brief review of ceramic problems as involved in the manufacture of porcelain for electrical purposes.

(e) Experiences and experiments in the practical use of the oscillator and the general methods of study of porcelain.

(f) Puncturing under oil: Thickness, range of puncture voltage, form of test piece.

(g) Equivalent gap tests.

(h) Voltage of first appearance of corona on insulators.

(i) Percentage of failure as a criterion of rejection.

(j) Comparison of puncture voltage of several porcelains.

(k) Technique of examination of cracks, laminations, punctures, etc.

(l) Hot and cold tests.

(m) Tests with continuous high frequency.

(n) Study of the effect of corrugating a smooth surface and the laws of creepage spark as affected by thickness of porcelain.

(o) Methods of using super-spark potential from the oscillator.

(p) Methods of examination of quality of porcelain, using voltage gradient.

(q) Determination of the proper time of test and something on the question, "Does the voltage test damage the porcelain?"

Much valuable work on electrical porcelain, comprised in a number of papers, has been presented to the American Institute of Electrical Engineers during the past few years. The recent steps taken by the committee on standardization of tests of insulators have had great value in crystallizing the known data and information into a definite useful form. It is here proposed to add further to the collected data and present a new method of testing insulators which the author believes should supplant the old standard method in which potential at a frequency of 60 cycles per second is employed.

It seems unnecessary to dwell at any great length on the engineering necessity of finding a satisfactory solution of the problem of maintaining the integrity of the insulation of electrical transmission lines. It is desirable to attack this problem from every available scientific and practical standpoint. The problems relating to the integrity of the insulator are only a part of the broad problem of continuity of service on transmission circuits. A brief review of the salient factors of the broad problems is given in the following analysis, in which the position of the problem of the insulator itself is made evident.

PART I. TESTING WITH A HIGH-FREQUENCY OSCILLATOR

2. Analysis of the Broader Problem of Continuity of Service

In the first consideration we can hope only to pursue the line of investigation relating to detection of weak and damaged porcelain insulators, and either reject them if they have not yet been installed or remove them from the line if they are already in use.

In the second consideration we may hope with confidence to overcome the causes which deteriorate the insulators after they have been put into use—such damage as comes from unequal expansion of metal parts, cements, and porcelains. This investigation should also cover those faults which are present in the manufacture, in one form or another, such as open pores, closed pores, cracks from unequal contractions, local strains, laminations, air pockets, localized mineral impurities, and accidental impurities in the form of threads and hair.

In the third consideration is the form of the insulator. The ideal design should be such that the porcelain shall never puncture.

In the fourth consideration is the way and means of preventing lightning from producing a potential sufficient to arc over an insulator. This involves the subject of overhead and under-hung grounded conductors; also the necessary factor of safety of the line insulator.

In the fifth consideration, assuming that in spite of all precautions an accidental arc is established around an insulator, what means may be employed to suppress such an accidental arc without causing or allowing an interruption of service? Herein comes the use of arcing ground suppressors and short-circuit suppressors.

In the sixth consideration is the condition of malicious or accidental interference with the power wires in which a heavy conducting strip is thrown across two conductors or two line wires are pushed together. The only possibility of continuing the service then lies in the use of a duplicate undamaged circuit and automatic relays to cause the nearest circuit breakers on both sides of the short circuit to open and thus remove the faulty circuit.

In the seventh and last consideration is the rare occurrence of cyclones, floods, and sleet storms which destroy considerable lengths of the circuit. The only insurance against interruption of the user's service is then a local steam auxiliary or storage battery.

In this paper we are concerned with the first three considerations and a part of the fourth consideration, all of which deal directly with the porcelain insulator.

3. How Should Insulators be Tested?

We have in the past tested insulators with high potential at the available frequency of 60 cycles. In suggesting testing with high frequency it becomes necessary to differentiate between the different kinds of high frequency that can be produced by different types of apparatus. There is the continuous high frequency as given by an Alexanderson generator and there is the high-frequency wave train produced by a discharge of a condenser through a transformer having no iron core. In each case there is the question of what value of high frequency to use and what potential. These factors will be considered more in detail later, but we can find immediate answer to the question of the proper tests to make by statement of the conditions to which the insulator is subjected. Insulators in practise may become faulty due to unequal expansion of metal, cement and porcelain, but even then they seldom get an opportunity to fail at 60 cycles because of the fact that every circuit has superimposed on the 60-cycle potential occasional higher frequencies coming from switching and variations in load which reach the gradually developing faults in the insulator before the deterioration is sufficient to be affected by the 60-cycle wave. This whole question of what conditions of potential and frequency to impose in test on an insulator can be answered in the general statement: *test the insulator under the same conditions which cause its failure in actual operation*. These conditions will now be reviewed.

4. Classification of Faults in Insulators

There are two entirely distinct conditions of failure between which we must differentiate. First, complete failure of the porcelain by cracks, leaving only air and moisture as insulation between the metal terminals of the insulators. There is no need to discuss refinements of tests in this case. The desired tests consist simply in furnishing sufficient voltage to break down the air gap in the crack of the porcelain. If there is moisture in the air gap an ordinary resistance test with a megger will show the presence of the crack. In the absence of moisture a higher voltage must be used. Second, flaws consisting of small cracks, laminations, air pockets, porosity, etc., in insulators which withstand the normal 60-cycle potential applied to them and even the higher value of 60-cycle test potential, but will fail under the imposition of high-frequency wave trains such as occur in lightning strokes, switching, etc.

NOTES ON TESTING OF INSULATORS WITH THE OSCILLATOR

5. Problem of Testing the Thousands of Insulators Already Installed

One of the most important points regarding the use of the oscillator lies in the fact that it can be made so light and inexpensive and easy to handle that it can be used by the transmission engineers and their assistants to test out insulators after they have arrived at their destination, and also to test out the thousands of insulators which have been installed during the past dozen years, and thereby to pick out the faulty ones.

6. THE CONDITIONS TO WHICH INSULATORS ARE SUBJECTED IN USE

In order to determine the nature of the desired electrical tests the following analysis is made. Insulators are damaged electrically, first, by lightning; second, by surges from switching; and third, by surges from accidental arcing grounds, and the like. The duration, voltage, and frequency of these surges will now be analyzed.

7. DURATION CHARACTERISTICS OF THE THREE KINDS OF SURGES

Lightning has the characteristic of momentary duration, but a stroke may be repeated a number of times in such rapid succession that the successive strokes appear to the eye to be one stroke. There are many records taken by moving photographic films which show conclusively that lightning does come in multiple strokes.

Switching surges are also of comparatively short duration, taking place only at the moment of closing or opening of the oil switch or the blowing of a fuse.

Surges set up by accidental grounds are frequently of considerable duration, lasting many seconds or even many minutes. Single-phase short circuits sometimes cause high voltage in other parallel circuits.

8. RISE OF VOLTAGE OF THE THREE KINDS OF SURGES, AND THE FREQUENCIES INVOLVED

In each case the rise of potential also must be considered as a factor of menace to the integrity of the porcelain insulators. In the case of lightning there is no limit to the potential except that which will cause a discharge from line to ground. In the case of switching, the voltage on the line nearly always reaches double value; and with changes of ratio of capacity and inductance in the transmission circuit or with partial resonance, the surges may rise to considerably more than double line potential. In the case of arcing grounds the voltage will usually rise to double value and there are many chances of a resonant condition existing which will carry it much above double value.

9. THE OSCILLATOR TESTING SET

The testing set, as developed, is shown in Fig. 1. It consists of the following elements as shown in the diagram, Fig. 2.

a. A 60-cycle step-up transformer.

b. A condenser placed across the terminals of the high-voltage coils of the transformer.

c. An adjustable gap.

d. An oscillation transformer, oil-immersed, without iron core, consisting of a few turns on the primary and many turns on the secondary. The regulation of this transformer is made as good as can be obtained and, unlike the wireless outfits, there is no dependence placed on obtaining resonance for the ordinary tests.

e. A sphere gap made up of spheres of diameter equal to maximum air gap.

f. A suitable reactor to protect the step-up transformer against the damaging effect of short circuit when a spark takes place on the small gap.

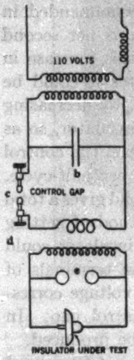

FIG. 2

Diagram of connections of the oscillator testing set for porcelain insulators.
b, condenser
c, control gap
d, oscillation transformer
e, sphere gap
f, series inductance

The ratio chosen for the 60-cycle transformer is 110 volts to 13,000 volts, as both are standard and 13,000 volts is high enough to give good effects in the oscillator, in the set large enough to test ordinary single-unit insulators. This outfit is capable of producing a voltage represented by a setting of 125,000 volts on the sphere gap and is capable of operating at this value all day long continuously. This is the testing set recommended for general use. For testing single lower voltage insulators a smaller set can be built to meet the special needs.

The main frequency of the natural oscillation of such an outfit without the secondary of the coreless transformer in place is about 200,000 cycles per second. The range of high frequency recommended for testing is 150,000 to 400,000 cycles per second.

The maximum rate of discharge should not be less than 1000 kv-a. This maximum rate of discharge is not dependent on the kilowatt rating of the 60-cycle transformer but depends mostly on the electrostatic condenser.

The foregoing data cover the characteristics of a testing set which is capable of testing most of the insulators in use. It is easily manufactured and satisfactory in operation. A convenient form is shown in the accompanying illustration, Fig. 1.

10. CONTROL OF VOLTAGE OF THE OSCILLATOR

The voltage is controlled by gradually opening the control gap shown in Fig. 2. One electrode of this control gap is connected to a long insulating rod which permits of handling while the arc across the gap is playing. In this way the voltage is gradually increased to the desired value while it is being applied to the insulator.

The control of the voltage by the use of the control gap alone gives a very simple condition and its use is recommended in spite of an increase in the number of wave trains per second at less than quarter its maximum voltage. If this increase in the number of wave trains were a serious matter it could be taken care of in either one of two ways. First, by decreasing the total time of applications of voltage to the insulator, so as to give the same total number of wave trains, when the control gap is small and sparking over more than one per half-cycle. A test of one minute with 120 alternations per second gives a total of 7200 wave trains per minute. The other method of getting a definite number of wave trains applied to the insulator could be accomplished by reducing the voltage at the terminals of the 60-cycle transformer, thus making the peak voltage correspond with the spark voltage setting of the control gap. In this way a single wave train per half-cycle will be produced.

As a matter of experience it is found that except in special cases the variation in the number of wave trains is not a serious matter in the practical testing of insulators. There are several factors involved. First, the time of rest of an insulator set at one minute or ten seconds is a quite arbitrary value and the period might well be chosen as two minutes if so desired. Two minutes would correspond to twice the number of wave trains per second. It is desirable to maintain the standard of one minute for test for reasons of economy. Second, the greater number of wave trains is produced at the lower values of voltage and the lower values of voltage correspond to small insulators on which there is a large factor of safety. As the matter stands, then, there is a greater number of wave trains applied to the lower voltage insulators, but they are capable of withstanding it and the extra number of wave trains applied for one minute is not sufficient to cause deterioration of good porcelain.

In Figs. 3, 4, and 5 are given three oscillograms taken in the 60-cycle circuit of the oscillator which show typical conditions for three different values of voltage generated in the secondary.

PLATE XXIX.
A. I. E. E.
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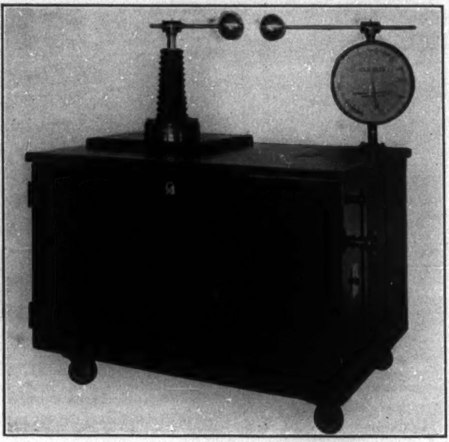


[CREIGHTON]

FIG. 1

125-kv. oscillator with sphere gap voltmeter. Single terminal of the coreless transformer shown at the left to which one sphere is attached. The other terminal of the coreless transformer is grounded. The other sphere which carries the voltmeter is grounded so that it can be handled while the spark is playing.

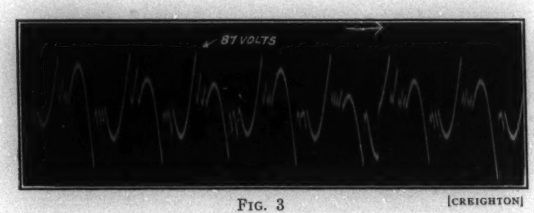


FIG. 3

[CREIGHTON]

Oscillogram of voltage in the 60-cycle circuit of the oscillator when the control gap is set for 6000 volts effective. There is only one main discharge at the control gap per half-cycle. When a spark at the control gap takes place it is indicated on the oscillogram by a sudden drop in voltage.

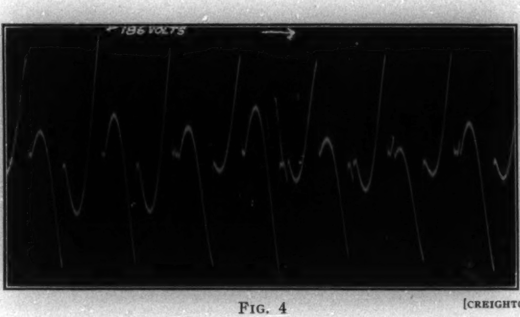


FIG. 4 [CREIGHTON]

Oscillogram of the voltage on the low side of the 60-cycle transformer when the control gap is set for 12,000 volts. There is only one main discharge at the control gap per half-cycle of the 60-cycle circuit.

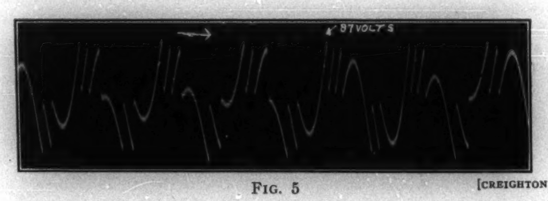


FIG. 5 [CREIGHTON]

Oscillogram of the voltage on the 110-volt side of the 60-cycle transformer. A blast of air was playing on the arc which removed the ionized gases and thereby introduced about three wave trains per half-cycle, all of which are about equal.

Comparing oscillograms of Fig. 3 and Fig. 4, it is seen that the voltage at the control gap may be reduced more than 50 per cent by decreasing the length of the control gap without increasing the number of wave trains per second which are effective in producing the high voltage on the secondary of the coreless transformer. In a 60-cycle circuit there are 120 alternations per second and the gap should spark over at each peak value of the 60-cycle potential. When the gap sparks over it is indicated on the oscillogram by a sudden drop. In Fig. 4 there are extra oscillations after the first peak value which re-light the spark but the voltage is so low, as compared to the peak value, that it is negligible.

In Fig. 5 an air blast is added which carried the ionized gases of the spark away and causes the voltage to rise to practically full value two or three times per half-cycle. The spark at the control gap is then extinguished and the voltage curve gradually drops into the regular 60-cycle wave, the distortion being due to the electromagnetic energy derived from the series reactance in the 60-cycle circuit.

11. MEASUREMENT OF VOLTAGE

The only available practical method of measuring the voltage of high-frequency wave trains is by sphere gap. Although the voltage may not be accurately expressed in volts, due to the unknown conditions of ionization and deionization at high frequency, and also due somewhat to the inevitable dielectrical spark lag, still there is no reason for not accepting the voltage measurement taken by the sphere gap. Since this statement may be open to question, a further analysis of the object we have in view and how it differs from other voltage measurements is given in an endeavor to clarify the situation. Under the ordinary conditions of power distribution for lighting it is quite essential to have a definite voltage which can be measured and relied upon in order not to damage the lamps to which the voltage is applied or to have the voltage so low as to get an insufficient amount of light. The object in view in measuring the high-frequency wave trains is not in any way similar. Therefore we do not need to have the same standard. The object in the measurement of the voltage, or more accurately stated, the equivalent sphere gap, of an insulator is the desire to know what potentials must exist at the terminals of the insulator to cause it to arc over or puncture. Although it would be of interest to express this tendency to spark over the insulator in terms of accurately expressed voltage, either peak value or effective value, it is not at all essential. The essential feature is to have a standard of reference with which to compare different types of insulators, different forms and conditions of electrodes, and such other features of design as produce the most reliable insulator. The sphere gap furnishes reliable means of measuring the limiting condition which will cause a spark to form over the insulator, and it is convenient to express the gap length in terms of the voltage which will cause the gap to arc over at the usual frequency of 60 cycles.

In choosing the sphere gap the diameter of the sphere is made about equal to the maximum gap length to be used.

There is another value of voltage that it is desirable to measure for the information it gives relative to lightning arresters; that is the minimum gap setting of the spheres which will take all the discharge away from the insulator. This minimum gap setting is considerably below the maximum gap setting which causes practically all the discharges to take place across the insulator. The intermediate values of sphere gap settings between the maximum and minimum are in general of no particular interest.

Instead of giving the equivalent sphere gap in centimeters or inches the values are translated immediately by means of the scale on the oscillator into equivalent kilovolts at 60 cycles. In some cases we have used a straight scale subdivided into kilovolts underneath the supporting rod of the grounded sphere. In another case we have attached a wire to the shank of the grounded sphere and passed this wire around a cam which carried a pointer around a circular dial as shown in Fig. 1. The large dial adds little to the expense but it has the advantage of being read more easily and is economical of time in testing.

For special conditions of study a dial has also been used on the control gap which measures the gap length. The ratio between the voltage on the control gap and the voltage produced on the sphere gaps will vary according to the load that is placed in parallel with the sphere gaps. However, for any fixed condition of load the control gap can be calibrated and used as a measure of the applied potential with a fair degree of accuracy. The control gap gives the maximum voltage generated and the sphere gap gives the maximum voltage that exists across the insulator, which is naturally less than the maximum super-spark voltage applied. The voltage measured by the sphere gap is somewhat above the spark voltage of the insulator when the voltage is gradually increased in the usual way. The dial, then, on the control gap has its special uses, although it is not an essential part of the testing outfit for the usual tests that have been made on insulators in the past.

12. Kilovolt-Ampere Capacity of the Oscillator

The kilovolt-ampere capacity of the testing apparatus is important, especially where a number of insulators is tested in multiple. The capacitance of the electrostatic condenser used with the coreless transformer, together with the inductance and regulation of the coreless transformer, determines the value of power which can be delivered by the testing outfit. The power of the oscillator is used up in producing corona over the surface of the insulator and its connecting wire. In the oscillator testing set designed for general use, there is sufficient energy to produce spark-over on five disk insulators in parallel when the electrostatic condenser has a capacitance sufficient to store up 500 microcoulombs. By doubling the capacitance it is possible to test ten suspension type insulators in parallel. The rating of this oscillator is 125 kv., which it can carry continuously. For short periods of testing it has been used up to 175 kv. on a single insulator. It is capable of producing for an instant approximately 5000 kv-a. A somewhat smaller outfit could be used for testing single insulators of the suspension type, but the smaller oscillator would have less application and would require a considerable knowledge of its characteristics and adaptability to prevent its being used under conditions which would give inadequate potential stress on the insulator.

We have in the laboratory an old Tesla coil outfit which is smaller, but the kilovolt-ampere capacity of this outfit was insufficient to spark over an insulator designed for a 33-kv. circuit. The corona, formed at the head of the insulator and extending out about an inch over the surface, absorbed all the available energy from this outfit far below arc-over voltage.

13. What can be Done with the Oscillator to Reproduce Operating Conditions of Insulators

The ideal criterion for testing is to weed out all insulators which will fail subsequently in use. Tests should be made to meet these operating conditions. The method of test using the oscillator adapts itself with a fair degree of perfection to the reproduction of all of these conditions and it is only a matter of choice on the part of the engineer to get with its use the mildest or nearly the severest conditions of electric surges. These different degrees of severity of test can be obtained with greater ease and simplicity than with the 60-cycle testing apparatus. There is needed no special motor-generator set, no fussing about sine-wave alternators, no question of limited kilowatt capacity due to the use of more or less resistance, no large transformer and separate means of excitation of the generator, etc. Two turns on the screw of the control gap give the full range of voltage, the maximum of which may be far above the arc-over voltage of the insulator and yet no short circuit is produced on the oscillation transformer, such as takes place in the 60-cycle transformer when a spark occurs. The other factor involved in the tests is the duration of application, which can, of course, be fully controlled by a hand switch.

14. Tests with the Oscillator with Six Gradations of Severity and Duration

A number of arbitrarily chosen tests graded in severity and time of application, which correspond to surge conditions in practise, are given below for illustration.

The first gradation, the mildest test with the oscillation transformer, consists in opening the control gap gradually until a slight corona appears on the insulator but keeping the applied high-frequency potential considerably below the value which will cause a spark around the skirts of the insulator. The corona is plentiful, audible, and visible in daylight, and therefore there is no difficulty in arriving at the desired degree. If this potential is applied for a very brief time it corresponds to a light induced discharge of lightning on the line, surges from switching, and the momentary arcing ground through enough resistance to prevent high potentials. This test is too mild to have any value except when the insulator is cracked or punctured.

The second gradation of testing is the application of this potential (somewhat less than the spark potential of the insulator) during a long period of time—say from one minute to five minutes. This test corresponds to a mild condition of sustained arcing ground. Insulators that will not stand this test would surely fail in service. The test is also too mild to consider for practical use.

The third gradation is obtained by opening the control gap of the oscillator so that the potential rises to a value sufficient to occasionally spark around the insulator—say once every second or so. Again this discharge may be applied for a fraction of a second, corresponding to dangerous lightning discharges, dangerous surges from switching and from momentary arcing grounds.

The fourth gradation consists in applying this discharge for a longer time, ranging from one second to five minutes, which corresponds to high-frequency surges generated by unusual conditions of vicious arcing grounds for a period corresponding to the duration of test. Such arcing grounds may or may not cause a short circuit which ends the application of high voltage. Applied for one second, the test corresponds to 120 lightning strokes in quick succession of a voltage equal to the arc-over voltage of the insulator or some lesser unknown number of strokes scattered over several years. The test is very mild as a substitute for lightning strokes, as they come, of various values of potential above the value which is necessary to cause a spark around the skirts of the insulator. A duration of one minute makes a fair test and is recommended as a tentative standard.

The fifth gradation consists in opening up the control gap of the oscillation transformer so that momentarily the oscillation transformer gives its maximum voltage, which should be a super-spark potential for the insulator. This voltage stress is applied to the porcelain during the brief time of dielectric spark lag that is required to form the spark around the skirts of the insulator or, otherwise, during the time necessary to puncture the porcelain. This test, applied momentarily, corresponds to a very heavy lightning discharge. It corresponds also to a rare case of switching and also to the accidental conditions where there is a cross between a high-voltage circuit and one of lower voltage. The application of a number of these single strokes is nothing more than the insulator may get in operation in due time. The surge potential corresponding to this test may not appear many times per year on a transmission system. Good continuous service suggests the test. Scarcity of good line insulators may not always permit the adoption of this as a commercial test.

The sixth gradation consists in applying this super-spark potential to the insulator for a longer period of time, of the order of 1 to 20 seconds. This latter test may very justifiably be considered from a conservative standpoint as more severe than is necessary, more severe than actually occurs as a rule in practise. It may, therefore, in the present state of development of insulators, be considered only as a comparative test to give the endurance of different types of insulators and may, consequently, be placed in the category known as a " design test."

15. TENTATIVE RECOMMENDED TESTS

There are special tests of unusual severity which it may be desirable to make as comparative between different types of insulators, but with these special tests we are not concerned at the present moment. After testing many insulators the following test has been adopted for the purposes of this investigation. Raise the potential rapidly about two kv. every five seconds until an occasional spark is produced around the skirts of the insulator, a spark about every second or so; hold this potential for one minute; then raise the potential by about 20 per cent, causing a flood of sparks around the insulator, and hold for ten seconds.

16. OPERATORS' VIEWPOINT AND EXPERIENCE

Mr. F. Osgood at the recent meeting of the Institute emphasized very strongly that the oscillator had shown bad designs of insulators on their system, resulting in the complete elimination of all the insulators of a certain type, and furthermore, he found weakness in all the older pin types of porcelain insulators. The manufacturers of insulators were asked to produce an insulator which would stand the high-frequency test and I understand they have been able to do it. This is a step toward perfecting the insulation of a transmission line.

17. WHEN IS THE OSCILLATOR TEST DANGEROUS TO PORCELAIN?

In answer to the criticism that the method of test is dangerous, it should be noted that the surges on the line are also dangerous to the porcelain, especially if it is faulty.

The object of the test is to make it dangerous to faulty porcelain. The object should be, and before long will be, to damage and destroy every insulator which in practise would be damaged by the surges in the circuits. It will finally be good economy to do this. If the test is made to correspond to the conditions on the circuit which the porcelain is designed to withstand, then the statement of danger has only a desirable significance.

18. RECOMMENDATIONS

Let us examine the subject in its several different aspects: 1st, old designs; 2nd, cracked, porous, or punctured porcelain of insulators already installed; 3rd, new insulators not yet installed.

First. We have not yet arrived at a condition of perfection of design of all pin insulators. Therefore, it is too early to recommend a wholesale slaughter of weak designs. Reasonable engineering judgment must be exercised in each system to weed out the insulators which are weak enough to fail under the *frequently* occurring surges of switching and accidental arcs; but the next better grade should not be damaged by too severe tests and should be left in place on the lines to run chances in escaping a heavy strain due to lightning, until the evolution of design and manufacture brings forth a more perfect insulator. The test of these old insulators in place should therefore be milder than it will eventually be desirable to make it. It is not difficult to get a conception of the possibility of damaging an insulator under test. A time test, as described later, made on a number of insulators will determine the possibilities of damage from the test.

If old insulators are mounted on wooden cross-arms and the pins are not grounded a much weaker insulator can be used successfully than where the pin is grounded. Still the cracked and punctured porcelains must be removed from the circuit, because a failure of the insulator causes the destruction of the supporting wood and is consequently a great menace which threatens long-continued interruption of service while a pole and arm are being replaced.

Second. In the case of porous or cracked or otherwise badly weakened porcelain the test must be severe enough to show the fault.

Third. In the purchase of new insulators the requirements of test should be severe enough to show faulty design and the presence of flaws which will subsequently be developed by the surges under service conditions. Rigorous tests should be used on new insulators before installation to determine definitely that neither the design nor the quality of porcelain is poor.

19. IS THE HIGH-FREQUENCY TEST DANGEROUS TO GOOD PORCELAIN?

The next question relates to the danger of the test to good porcelain. Every test which carries the electric strain up to the maximum limit of the porcelain is very liable to cause danger even to good porcelain. If, as it should be, the thickness of porcelain is made such that the spark potential around the skirt is very much less than the puncture potential and the design is so made that the potential gradient at any point has a reasonable value, less than the damaging value, then the recommended high-frequency tests can be made without damaging good porcelain. If many insulators fail it may be an indication that they are too near the danger limit of electric stress. In further reply to this criticism, it should be recalled that the results of tests on 60 cycles have shown that the 60-cycle potential at spark-over value may also damage porcelain.

In a paper presented to the A. I. E. E. June 1911 by Mr. Austin, he showed that the 60-cycle potential applied to a rack of insulators would puncture quite a number of them during the first period of a few minutes and would continue to puncture insulators during every minute that the test was continued, although at a lesser number per minute as time went on. From this it is evident that at the end of a minute test there will necessarily be some porcelain insulators which are just ready to puncture and may be in a condition described as damaged. Familiarity with the rule of one minute duration of test may cause the critic to overlook this condition. The subject will be somewhat clarified by the observations on the nature of flaws given later.

Since 1911 there has been very evident progress made in the manufacture of electrical porcelain. From our observations on the use of high-frequency potentials for testing insulators it would appear that defective insulators would be picked out earlier by the high-frequency tests and our test results show that batches of suspension insulators delivered to the laboratory have withstood high-frequency tests by the hour without losing a single insulator among them. Some tests were run continuously nine hours per day for six days with the voltage at barely arc-over value, and the insulators are still in good condition. This experience tends to show that only the faulty insulators will be picked out by the tests.

This question of damage to good porcelain in particular cases can be determined sometimes by special tests on insulators. If an insulator is tested continuously for an hour without puncturing, it is reasonably evident that a one-minute test will not damage the same porcelain and a test limited to a few seconds gives still further assurance. The question then of the duration of test and the damage that results thereby can be determined on special lots of insulators by the number that is damaged in a given time, which should be made long as compared to the standardized duration of test. Our own results show that an insulator of good design and good porcelain will withstand high-frequency discharge many hours. In thus comparing two different designs of insulators or two different makes of insulators, it is evident that one that withstands the discharge for the longest time will be the better insulator to use. If many insulators under test are shown to be damaged by a reasonable test it is evident that the design is faulty or the porcelain defective. If the test is made less severe than reasonable, then poor insulators will be installed on the line. With poor insulators installed, it becomes a matter of chance how soon they are caught by a surge. On the ideal line there should not be used a single insulator that will puncture.

20. PORCELAIN IS NOT HEATED BY NORMAL TEST WITH THE OSCILLATOR

A criticism of the method has been that the high frequency entails dielectric losses which it is feared will damage the porcelain. There is no doubt that the high-frequency test produces more heat in the porcelain, by some sort of hysteretic effect, than comes from the application of 60 cycles. There is also no doubt that the high frequency will reach and damage a bad spot much more quickly and much more surely than the 60-cycle tests. In regard to this heating, however, there should be no confusion between the application of high-frequency wave trains at 300,000 cycles from an oscillator and high frequency from a generator. In the case of the oscillator a wave train of high frequency is applied about 120 times per second. Between adjacent trains there is a relatively long period of rest, about 100 times the duration of a train, during which no potential is applied to the insulator. On the other hand, when the potential is supplied by a high-frequency generator, the high frequency is absolutely continuous and the heating of the porcelain is correspondingly magnified. With continuous high-frequency voltage it is possible to overheat the insulator and damage it by heat alone. Even under continuous frequency nearly all the heat comes from corona in the air and very little from dielectric hysteresis in the porcelain.

In conclusion, long-continued tests have shown that there is no danger of hysteretic heating of good porcelain insulators by the recommended tests using the wave trains of an oscillator.

21. HEATING OF THE SURFACE OF THE INSULATOR BY CORONA AND SPARKS

As to the damage from heating the surface of the porcelain, it can be stated in general that the corona may take place over periods of several minutes without heating up the porcelain more than a few degrees. It is hardly perceptible to the touch. The sparks have more heating effect but nothing serious—a rise of a few degrees. There is one undesirable condition, however, which will be perfectly evident to the tester: When, due to using very heavy discharges, the spark concentrates in one fixed streak around the porcelain skirts, local heating can take place on the surface of the porcelain. This concentrated heat will usually crack the porcelain in a minute or so. This fixed spark is an improper application and can be avoided by changing the conditions of test. It should be understood that the proper testing of the insulator by high frequency consists in making the discharge take a new path around the insulator at each successive discharge, so that the appearance to the eye is that of many radial streaks of discharge fairly uniformly distributed over the whole surface of the insulator.

22. CHARACTERISTICS OF THE 125-KV. HIGH-FREQUENCY OSCILLATOR

Much of the detail work of making a practical design of oscillator has been done by Mr. P. E. Hosegood. There are certain complex phases of the problems involved which are out of the scope of the present presentation. However, the important characteristics of the oscillator from a useful standpoint have been summarized by Mr. Hosegood and are herewith presented, with the addition of only an occasional comment by the writer intended to connect the information with the rest of the paper.

One of the chief objects to be achieved in the design of a high-frequency oscillator for testing insulators is good regulation so as to be able to test a number of insulators at once without undue drop of voltage. When insulators are connected to the oscillator the voltage falls off due to regulation. The current in the high-voltage coil supplies two conditions, viz: the loss of energy in brush discharge and the capacitance of the insulators. These conditions call for as close a coupling between the two coils of the oscillator as can be obtained. Owing to the variation of the capacitance of the high-tension circuit of the oscillator, with varying loads, it is impracticable in general work to use loose coupling between primary and secondary, and depend on adjusting the inductance and capacitance for resonance. With close coupling, the voltage generated at the high-tension terminal of the oscillator will depend chiefly on the ratio of turns between primary and secondary windings of the coreless transformer.

The voltage applied to the condenser depends upon the setting of the control gap. The preferred form of control gap consists of two wheels rotated by a motor. The spark takes place between the peripheries of the two wheels. This arrangement reduced the wear caused by the spark and also maintains the spark potential at a constant value for any given length of spark gap.

Figs. 3 and 4 show oscillograms of the potential across the 110-volt primary of the 60-cycle transformer. In Fig. 3 the control gap is set for 6000 volts effective, and in Fig. 4 for 12,000 volts. The latter is the maximum rating of the condenser. It will be noticed in both cases there is only one high-voltage spark for every half-cycle. When the spark takes place, it short-circuits the high-voltage side of the 60-cycle transformer, and a sudden decrease in voltage across the primary occurs. The primary source of power is not short-circuited but the voltage is momentarily shifted from the 60-cycle transformer to the series reactance shown in Fig. 2. It is only at very low settings on the control gap that the number of wave trains per half-cycle of the 60-cycle circuit increases materially. At low voltage it makes comparatively little difference in the effects obtained if the number of wave trains per second does increase.

In Fig. 5 an air blast is applied to the control gap, which was set at 6000 volts. Two or three full-voltage sparks occurred every half-cycle. This materially increases the average current in the oscillator. With the air blast playing on the gap the number of sparks per half-cycle varies according to the length of control gap.

The curves of Fig. 6 give a measure of the oscillating currents in the high- and low-tension coils of the oscillator at various settings of the control gap, the high-tension coil of the coreless transformer being short-circuited. The values of the control gap were obtained by calibrating the gap with 60-cycle voltage. The values of current increase with the control gap. This increase is not directly proportional, as the resistance of the spark increases with the length of control gap, causing more rapid damping of the oscillations of each wave train.

The no-load characteristic is shown in Fig. 7, curve *A*. The normal voltage rating of the oscillator, 125 kv., is obtained at no-load with a control gap setting of 5 kv., which is less than half the available voltage. Curves *B*, *C*, *D*, *E*, and *F* were taken with varying numbers of suspension type insulators connected in parallel to the terminals of the oscillator. With only one insulator connected, the arc-over voltage of the insulator is 85 kv. This arc-over voltage decreases when more insulators are added in parallel, due no doubt to the combined effects of the local oscillations coming from the corona on the surfaces of the parallel insulators and the difference in the arc-over voltage of the several insulators. With five insulators, the arc-over voltage measured by the sphere gap was 77 kv. These

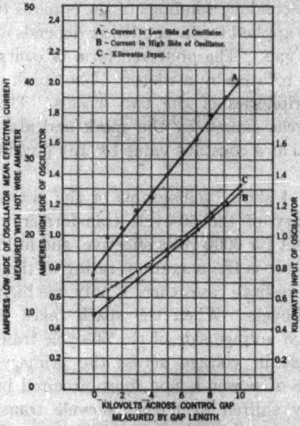


FIG. 6

Shirt-circuit characteristics of a 125-kv. oscillator. Top curve (A) is the relation of kilovolts across the control gap versus the effective current in the low side of the coreless transformer when the high side of the coreless transformer is short-circuited. Bottom curve (B) is the relation of the kilovolts across the control gap versus effective amperes on the high side of the coreless transformer. The current was measured by hot-wire meter. The middle curve (C) is the relation of the kilovolts across the control gap versus the kilowatt input of the oscillator measured on the 60-cycle side.

curves are practically parallel, and their different locations are due to the change of voltage ratio of the coreless transformer caused by the capacitance and corona at the insulators.

The effect of this load on the regulation of the oscillator is illustrated in Fig. 8, which shows the voltage obtained with varying numbers of insulators connected to the oscillator while maintaining the control gap constant. The voltage drop amounts to about 40 per cent from no load to full load, five insulators corresponding to full load for the condenser used in the oscillator.

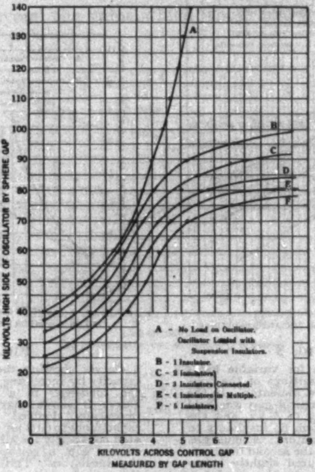


FIG. 7

Voltage generated by the 125-kv. oscillator in terms of control gap setting. Top curve (A), no load on the coreless transformer. Second curve (B), load of one suspension insulator. The third curve (C), load of two suspension insulators in multiple. The fourth curve (D), load of three suspension insulators in multiple. Fifth curve (E), four suspension insulators in multiple. Sixth curve (F), five suspension insulators in multiple.

The number of insulators that can be tested in multiple is directly proportional to the capacitance of the condenser in the low-tension circuit of the oscillator. This is illustrated in Fig. 9. By doubling the capacitance, the number of insulators that can be tested is increased from five to ten. The addition of capacitance to the oscillator lowers the frequency so that the output of the oscillator is limited by the minimum permissible frequency. The output can also be increased by raising the voltage applied to the condenser. However, the voltage necessarily increases more rapidly than the number of insulators that can be tested, so that the more efficient way to increase the output of the oscillator is to increase the capacitance of the condensers.

Fig. 10 shows the load curve for the 125-kv. oscillator, with the insulators connected in multiple in strings of two in series.

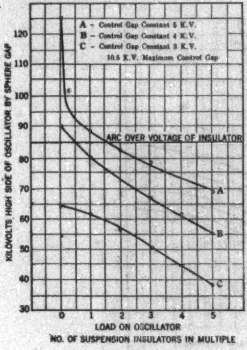


Fig. 8

Voltage regulation for variable loads with three different settings of the control gap on the 125-kv. oscillator. In the first curve (A) the control gap was held constant on a setting of 5 kv. and the load was increased from no insulators to five suspension insulators in multiple. At the addition of the second insulator the voltage was reduced slightly below the arc-over voltage of the insulator. Curve B is for a 4-kv. setting of the control gap, curve C for a 3-kv. setting. The maximum possible setting of the control gap in this oscillator is 10.5 kv.

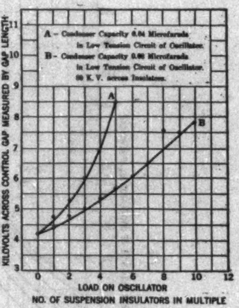


Fig. 9

Curves showing the gain in kilowatt capacity by increasing the capacitance of the condenser in a 125-kv. oscillator. Curve B shows that the load can be practically doubled by doubling the capacitance to 0.08 mf. There was generated constantly for all values of load and control gap, a voltage of 80 kv. across the insulators. This is slightly below the arc-over voltage of the insulator but sufficient to give extremely heavy corona.

The control gap was set at 16.5 kv., which is beyond the rating of the condenser supplied with the standard outfit. In addition, an air blast of about $\frac{3}{4}$ of a pound per square inch was used. The regulation in this case was 18 per cent drop from no load to a load of 16 insulators. The current supplied to the insulators was measured with a hot-wire ammeter. This current increases with the number of strings of insulators added, about 50 milliamperes for each string added. The input of the low-frequency transformer was measured and remained constant at two kw.

23. NATURAL FREQUENCY OF THE OSCILLATOR

The frequency of the wave trains in the low-tension circuit of the coreless transformer, having the secondary coil removed, was measured with a cymometer. The search coil of the cymometer was loosely coupled electromagnetically with the low-tension circuit of the coreless transformer. The capacitance of the cymometer was then varied until the maximum voltage was obtained, which was indicated by a small lamp. This frequency is 220,000 cycles per second. The high-tension coil of the coreless transformer was then replaced and the sphere gap opened beyond the value which would allow a discharge to take place. The two frequencies of a close-coupled circuit were then obtained, which were 238,000 and 508,000 cycles per second. With a load of five insulators on the oscillator only one frequency could be detected, which was 360,000 cycles per second. The reduction in maximum frequency from 508,000 cycles per second to 360,000 cycles has apparently no practical bearing on testing. If the higher frequency were prominent it should lower the spark voltage. As a matter of fact it has just been shown that the contrary condition exists: increasing the load lowers the equivalent sphere gap.

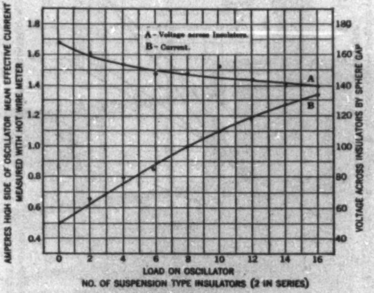


FIG. 10

In these curves the control gap was set at a constant value of 16.5 kv. with an air blast playing on it. It is an abnormal condition for the 125-kv. oscillator.

The load on the oscillator consisted of two suspension insulators in series and adding these as units. By so doing higher voltage was available than when one disk alone was used. The upper curve shows the decrease in voltage on the insulators as the load is increased. The lower curve shows the increase in current in the insulators due to the high-frequency wave trains as the load is increased.

Setting aside the possible effects of local surges between the parallel insulators, the change in natural frequency, as measured by the cymometer, has the effect, if any, of having increased from the minimum value of 238,000 to 360,000 cycles per second. There is no question at issue at present in this matter of frequency and voltage measurement. It is admitted that the theoretical problems, as a whole, are complex. There is involved dielectric spark lag for jump sparks and creepage sparks, and a consideration of each as it is affected by frequency, wave front, logarithmic decrement, energy in the corona, potential gradient, etc. All of these things are beside the point and beyond the scope of this paper. The same problems apply to 60-cycle circuits but the advocates of 60-cycle testing of insulators do not bring them into the discussion. The point is this: we are not directly concerned with the voltage which causes an insulator on a line to fail and thereby interrupt the service and damage the apparatus. The insulator must not fail. An insulator may pass a 60-cycle test but fail on a spark-over test from the oscillator. They are probably never strained

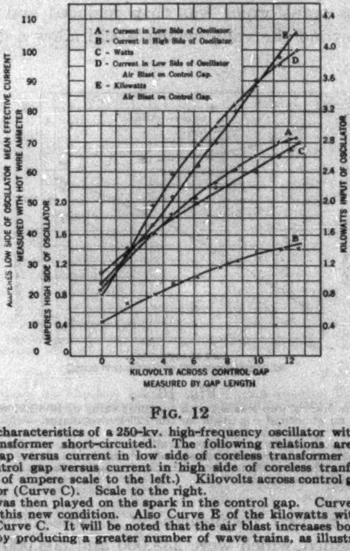


FIG. 12

Short-circuit characteristics of a 250-kv. high-frequency oscillator with the high side of the coreless transformer short-circuited. The following relations are given: Kilovolts across control gap versus current in low side of coreless transformer (Curve A). Kilovolts across control gap versus current in high side of coreless tranformer (Curve B). (Smaller values of ampere scale to the left.) Kilovolts across control gap versus kilowatt input of oscillator (Curve C). Scale to the right.

An air blast was then played on the spark in the control gap. Curve D corresponds to Curve A under this new condition. Also Curve E of the kilowatts with the air blast on corresponds to Curve C. It will be noted that the air blast increases both the current and kilowatt input by producing a greater number of wave trains, as illustrated in Fig. 5.

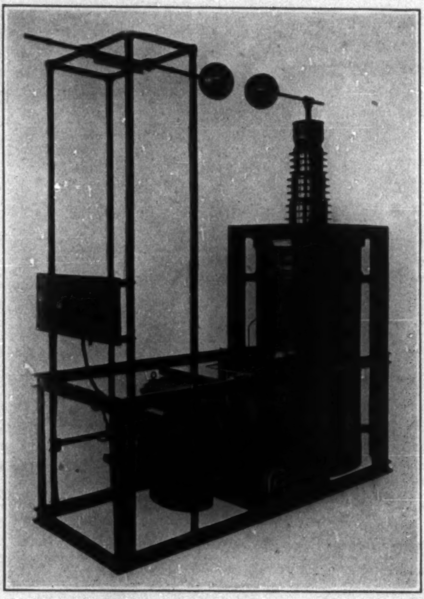


FIG. 11 [CREIGHTON]

The 250-kv. high-frequency oscillator. A small switchboard is mounted on the frame of the grounded sphere. Just below is a wheel for regulating the control gap. Above is the scale giving the value of kilovolts for the different settings of the sphere. Back of the corner post is the series reactance. To the right is the 60-cycle transformer. Still further to the right in the foreground is a small motor belted to the revolving wheels of the control gap. Back of the motor are the electrostatic condensers and to the right is a large coreless transformer supporting one sphere and having its other terminal grounded.

in use on the line with a voltage at 60 cycles because their factor of safety places the operating voltage at a relatively small fraction of the arc-over voltage. When they are strained by voltage it is a high-frequency impulse or wave train very similar in form and natural frequency to the wave trains generated by the oscillator. The wave trains in a transmission circuit will vary over a wide range of frequency but they will not differ as much in frequency from the oscillator as they do from 60 cycles, by more than a thousand times.

24. 250-KV. HIGH-FREQUENCY OSCILLATOR

The general appearance of this oscillator is shown in Fig. 11, the construction being similar to the 125-kv. oscillator. The coupling between the high- and low-tension coils of the coreless transformer, however, is not as close, as more insulation is necessary between coils. The short-circuit characteristics are shown in Fig. 12. These are similar to those obtained with the 125-kv. set. The effect of an air blast on the spark in the control gap in increasing the current in the oscillator coils and the watts input, is shown in curves *D* and *E*. The current is increased about 40 per cent.

Fig. 13 shows the no-load characteristic. For small values of control-gap setting the air blast increases the voltage obtained on the high side of the oscillator. This is probably due to the cooling effect of the blast raising the spark potential of the control gap. For higher values of the control-gap setting this effect becomes less noticeable.

Curves *B* and *D* show the effect of connecting to the oscillator a 70-kv. oil-filled transformer bushing. These curves begin to bend over at about 230 kv. owing to the rapid increase of the brush discharge as the arc-over voltage of the bushings is approached. This arc-over voltage is about 245 kv.

PART II. THE PROBLEMATICAL POINTS OF MANUFACTURE

25. THE MANUFACTURE OF ELECTRICAL PORCELAIN

In the order in which the work described in this paper was done, various experiences in testing porcelain with the oscillator should come next, but to understand the results of the experiments a knowledge of the characteristics of porcelain in its various stages of manufacture is quite essential. Therefore the processes of manufacture will be mentioned before continuing with the experiences of testing.

The object of this part of the paper is to endeavor to bring together the elements of scientific ceramics as they relate to porcelain for electrical purposes, eliminating all products pertaining to various other industries.

The natural aim is to improve the integrity of the insulators. Simply put, it is desirable to have an insulator which will never puncture nor break and if the potentials from lightning get beyond its dielectric strength the insulator must spark over through the air without puncturing the porcelain. To attain this end, many complex and unsolved problems must be considered.

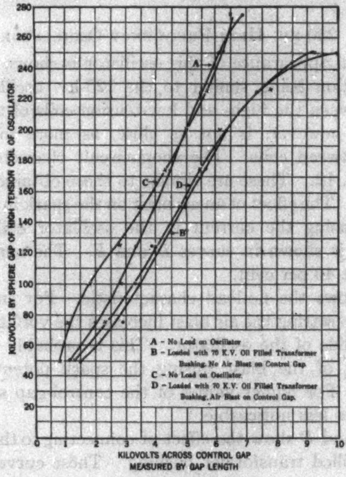


FIG. 13

The relation of kilovolts across the control gap to the kilovolts on the high-tension side of the coreless transformer as measured by sphere gap.

Curve A, no load on oscillator. Curve B, loaded with one 70-kv. oil-filled transformer bushing.

An air blast was then played on the spark of the control gap and curves C and D were taken. Curve C, no load on oscillator, as in Curve A. Curve D, same load as in Curve B. It will be noted that except at low values of control gap the air blast had very little effect on the voltage generated. In general, with the revolving wheels for control gap, the air blast will change the number of wave trains without changing materially the voltage.

26. DESIRABLE QUALITIES IN A PORCELAIN INSULATOR

1. It shall be mechanically strong in compression and tension.
2. It shall be tough, not brittle or fragile.
3. It shall be non-porous.

4. The porcelain shall be without appreciable cracks, laminations, cavities, conducting flaws, or air pockets.

5. It shall be of a fair, uniform dielectric strength.

6. It shall have a permanent glaze without cracks, roughness or checks to hold dirt in the surface. It is desirable to have the glaze as non-hygroscopic as it is possible to obtain without sacrificing other factors.

7. Incidentally the coefficient of expansion of the porcelain should be low in order to permit of sudden changes of temperature due to the weather conditions.

8. The parts should be held together with non-changeable cement.

9. In the matter of design the general rule to follow should be to keep the distance between the metal electrodes as great as the mechanical strength will permit. In general this rule calls for thicker porcelain than can be economically manufactured.

10. The design should be such that the air around the insulator is weaker to puncture than the thickness of the porcelain, even under super-spark potentials.

11. The design should be such as to give a relatively long drip space for water so as to hold a high value of spark-over potential during a rain.

12. For dusty countries extra lengths of creepage surface should be provided.

It is far easier to state what is desired than it is to make definite recommendations of how the desiderata are to be obtained. Every possible avenue of investigation should be tried until the desired perfection of insulator is reached.

27. LITERATURE ON PORCELAIN

Most of the literature on ceramics treats of pottery from an artistic and historic standpoint. One must read hours to pick up a few grains of useful information on the electrical porcelain intended for engineering purposes. One long book, containing over 700 pages on the manufacture of ceramic materials, devotes only one half page to electrical porcelain. The Encyclopedia Britannica devotes many pages to what can be seen on the surface of some specimen handed down from the nations of antiquity. These specimens range in technical skill of manufacture from the sun-dried pot, through the grade of soft porcelain, and finally to the most difficult, namely the art porcelain composed of kaolin, or china clay.

The writers on porcelain have not yet recognized that the modern electrical porcelain involves more attention to the form of the parts than the most fastidious Greek ever gave his. If in the ancient Greek art the curves were poor it displeased some of the cultivated eyes—that was all. If in modern electrical porcelain the curves are poor, thousands of people are deprived of light and power—which might be conceded as a more serious matter.

Electrical porcelain is an art of the present decade—an art in the making. The author has spent much time culling out of the mass of literature on the civilization-old art some of the pertinent factors relating to electrical porcelain, and it is thought that such condensed information is of value to others who are interested but have not the time or opportunity to cover the subject.

While making tests under new advantageous conditions the information has been brought to the attention of ceramic engineers, and it is hoped, through this system of checking, that inaccuracies regarding the porcelain manufacture in any of the essential parts have been avoided. The difficulties of getting definite information on porcelain will be fully appreciated only by those who have tried. In our own meetings we have even been advised as electrical engineers to leave this difficult subject to the particular man who fires the porcelain part. For the electrical engineer a cloud of mystery is thrown around this work. The desire to maintain trade secrets has obscured processes which are universally used. Either a knowledge of some of these processes must be furnished to the electrical engineer to interpret intelligently his electrical tests, or else the ceramic engineer must fully master the electrical problem of design and produce the finished satisfactory insulators. One naturally turns to the Proceedings of the American Ceramic Society for information. In the Annual Report of the Board of Trustees the statement is made that, " Our industries are most of them old, and most of them have been and still are administered upon a mistaken policy of secrecy as a necessary condition of success. Very few practical ceramic chemists and works managers will tell what they know of their own branch of the industry."

28. DRY PROCESS VERSUS WET PROCESS

Dry Process Porcelain. We are not concerned herein with all grades of electrical porcelain. Porcelain for electrical purposes is divided into two quite distinct grades, known as *dry process* and *wet process* porcelain. As indicated by the names, they differ in manufacture mostly in the way the porcelain pieces are formed into the desired shapes. In the dry process, the raw mixture is in the form of slightly moist granular particles containing about 20 per cent of moisture by weight. These moist particles having the appearance of granulated or grated cheese, and are made to cohere in a moment into a handleable soft mass by being subjected to a high mechanical pressure in a mold. This pressure, no matter how great, does not squeeze out the entrapped air between the particles and furthermore, under the usual conditions of firing the open pores still remain. As a result, dry process porcelain is electrically only about equal to air in its dielectric strength. To get mechanical strength, the thickness of the porcelain parts is usually great enough to give safe dielectric strengths of the order of a thousand volts. When the voltage impressed on this porous dry process porcelain is several thousand volts the potential gradient at sharp corners of the electrodes is sufficient to start a molecular bombardment of the air in the pores. As a result the porcelain becomes heated, its ohmic resistance rapidly decreases with temperature and there is added to the heat of corona, the I^2R losses. If the dry process porcelain is used on high voltages it is used as a mechanical support but not as an insulator.

Wet Process Porcelain. The wet process porcelain is deposited in the form of a plastic cake, as will be described later, and although this cake becomes quite porous when it is dried out, the size of the pores, or the spacing between particles, is much smaller than in the dry process piece; consequently these particles can be cemented together in the kiln by the flux when the temperature reaches the melting temperature of the flux. Looking at the condition from a slightly different standpoint, each grain of the dry process material is made up of many fine particles of the same size as in the wet process and each grain becomes fairly well cemented into a solid vitrified mass, but the separate grains of the dry process are vitrified together only in those touching points that are near enough together to be connected by the softened flux at high temperature. In the shrinkage many irregular masses are pulled slightly apart, leaving not only open pores but open streaks which are easily observed with the naked eye by first soaking the porcelain piece in red ink, (or better still aniline stain in alcohol), and subsequently breaking the porcelain piece into fragments.

29. THE INGREDIENTS OF ELECTRICAL PORCELAIN

The three main ingredients of electrical porcelain are feldspar, clay and silica.

The feldspar constitutes a large portion of granite rock. After the granite is crumbled a certain amount of free feldspar results. There are three feldspars which exist either separately or more or less mixed mechanically and chemically in the mines.

1. Potash feldspar, known also as common feldspar or the mineral orthoclase. It consists of potassium, aluminum, silicon, and oxygen. $K_2\,Al_2\,Si_6\,O_{16}$

2. Soda feldspar—a tersilicate of soda—a mineral known as albite or indianite. It contains sodium, aluminum, silicon, and oxygen. $Na_2\,Al_2\,Si_6\,O_{16}$

3. Lime feldspar or unisilicate of calcium—a mineral known as anorthite, consists of calcium, aluminum, silicon, and oxygen. $Ca\,Al_2Si_2O_8$. The most important of these three feldspars for electrical work is potash feldspar.

When the feldspars are disintegrated or separated into their respective constituent oxides they have the following chemical formulas and percentage of weight.

		Potash	Alumina	Silica
Potash feldspar	Molecular properties	K_2O	Al_2O_3	$Si\,O_2$
	Percentage weight	16.9	18.4	64.7 = 100%
Soda feldspar	Molecular properties	Na_2O	Al_2O_3	$Si\,O_2$
	Percentage weight	11.8%	19.6%	68.6 = 100%
Lime feldspar	Molecular properties	$Ca\,O$	Al_2O_3	$2\,SI\,O_2$
	Percentage weight	20.1%	36.8%	43.1 = 100%

30. CLAYS

The two clays used as main constituents of porcelain are ball clay, and china clay or kaolin. The chemical analyses given of the clays differ from each other very little, yet the properties or characteristics of these clays in the practical work of manufacture differ greatly.

The important physical quality which distinguishes the clays is their degree of plasticity. The physical and chemical conditions which give the clays their plasticity seems to be a mooted question still among the ceramists. The particles of clay are exceedingly small. They are sometimes spoken of as colloids. The plastic clay has an unctuous greasy feel when rubbed.

Although the cause of plasticity cannot be given, the quality itself is familiar. By plasticity, as used by ceramists, something more is meant than that quality of allowing a change of dimensions by kneading while maintaining the particles in cohesion such as exhibited by light bread dough. There is meant or implied that after the water, mixed with the clay to render it plastic and pliable, is dried out, the particles of clay will not crumble into dust but will remain in a sufficiently solid condition to be handled without breakage. A variation in the relative weights of water is needed to render the clays from the several different mines plastic. The china clays and kaolins have not a high degree of plasticity and therefore there is added to them ball clay, which has the highest degree of plasticity. A piece of soft ball clay can be rolled into a long round coherent thread or rope without breaking. After the raw porcelain is dry it must retain sufficient coherence not only to hold itself together but also the ground-up particles of feldspar and flint, neither of which possess sufficient plasticity to give much aid. All the clays lose their plasticity after being heated above a few hundred degrees centigrade. It should be recognized that plasticity and coherence are among the most important qualities of raw porcelain. Many of the flaws are developed in an incipient degree before the porcelain goes to kiln.

The word kaolin is a corruption of a Chinese name for the locality where the china clay was obtained for the ancient industries. Kaolin, the clay, has an essential ingredient, the mineral kaolinite. The formula for kaolinite is given in several forms. It seems evident that the molecular structure varies greatly according to the material from which the kaolinite was formed.

Kaolinite is composed of hydrogen, aluminum, silicon, oxygen, and water of composition. The chemical formula is written as follows: $H_2Al_2Si_2O_8 + 1H_2O$.

When the kaolinite is considered from the standpoint of the resulting product, after it is disintegrated, its composition is given in terms of its oxides, namely alumina, silica, and water, in the formula Al_2O_3, 2 $Si\ O_2$, and 2 H_2O. The proportion of each of these is given in percentage directly below the corresponding formula.

	Alumina	Silica	Water
By formula..................	Al_2O_3	2 $Si\ O_2$	2 H_2O
By relative weight............	39.8%	46.3%	13.9%

Kaolinite is derived from the disintegration of feldspar in granite rocks which is brought about by the action of the elements, air, water and temperature.

Granite consists of the minerals orthoclase or microcline, mica, and quartz.

Silica, SiO_2, silicon dioxid, silicic oxide, quartz, flint, crystalline silica and sand are all used synomymously in relation to porcelain manufacture. All of these materials are nearly pure silica in slightly different molecular form and different in the nature of their small impurities. In general this constituent of porcelain is called flint, although in many porcelains ground-up quartz sand is used. Of the other silica materials which are not used but which are high in silica there is the precious stone opal, which has a higher content of water, infusorial earth, and float stone.

If we turn to the chemistry on these three materials we learn that the feldspar is used as a flux on account of its content of potash or soda. Flint and quartz alone are very refractory materials and are not affected by the temperature of 1350 deg. cent., the approximate value of the temperature of a porcelain kiln. Quartz is not attacked by acid, with the exception of hydrofluoric. Boiling alkalin solutions scarcely affect it. Flint, however, dissolves more readily in boiling solutions of the alkalin hydroxides. All the varieties of silica, however, when heated to redness with the alkalis, such as potash K_2O or the alkaline carbonites, combine with the bases, forming silicates which enter into fusion at a high temperature and solidify to a vitreous mass on cooling.

It is this solvent action of the potash of the feldspar on the quartz or flint which produces the solid porcelain mass. The greater the quantity of feldspar or flux the greater the tendency to vitrify. Combinations of clay and silica containing very little flux require extremely high temperatures to vitrify—several hundred degrees above the value usually obtained in the porcelain kiln. A definite idea of the softening temperature of the different compounds is furnished by the Seger cones which are used to measure the vitrifying condition in the kilns. These cones consist of the different minerals made up in a triangular pyramid, having a width of 9/16 in. at the base, 1/16 in. at the top and an over-all height of 2⅞ in. The catalogue of the manufacturer of the cones gives a complete list of ingredients with the corresponding temperatures they represent.

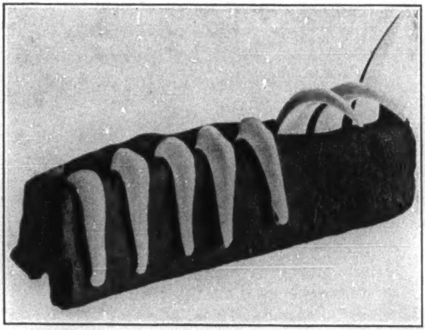


FIG. 14 [CREIGHTON]

Fired Seger cone showing the five lower cones entirely wilted, two cones part way down and one cone still standing almost vertical. (Bulletin 53. By courtesy of U. S. Department of the Interior.)

Several of these cones, Fig. 14, differing by one number, are placed side by side as a unit, and are located in different parts of the furnace where it is desired to measure the temperature. As the temperature reaches the melting point of each cone it deforms by bending over like a wilted plant. These cones under the high temperatures of the furnace droop to different degrees and the one that is not deformed at all represents the temperature or limit of the vitrifying tendency of the furnace.

To obtain a porcelain which will vitrify at different temperatures it is in general necessary only to change the content of potash or soda. It may be done also by using a feldspar containing both potash and soda in combination, as the two together seem to have a greater solvent action than either one alone.

Lime feldspar is used not at all or only sparingly. Lime is one of the chief ingredients of common glass and apparently has undesirable qualities in porcelain.

31. THE PROPORTION OF DIFFERENT MINERALS FOR PORCELAIN AND THE DIFFICULTIES IN OBTAINING AND MAINTAINING THESE PROPORTIONS DUE TO THE GEOLOGICAL CONDITIONS AND METHODS OF MINING

A standard mixture for porcelain for testing purposes is given as feldspar 20 parts by weight, quartz 30 parts by weight, kaolin 50 parts by weight. In Bulletin 53 of the Government Bureau of Mines, Mr. A. S. Watts states that the role of kaolin in all pottery mixtures is that of a plastic bond. It continues to hold the material together through the drying process. In firing, the kaolin, by its high refractory value and its resistance to the solvent action of the feldspar, enables the mass to retain its form although the particles of kaolin may be enveloped in fluid feldspar so completely that the mass becomes translucent and appears homogeneous.

The ingredients of porcelain as received in the mineral state by the porcelain manufacturers are liable to considerable variations both in their chemical contents and in the molecular form in which they exist. One cannot understand the difficulties of porcelain manufacture without a comprehension of the methods and conditions of mining the minerals. The change of material sold by the same name and giving the same chemical analysis in a porcelain factory is usually not carried out within a year after the change is contemplated as it requires a very long time to learn the methods of handling the new material in the many different forms in which electrical porcelain parts are made. In Bulletin 53, on mining and treatment of feldspar and kaolin in the Southern Appalachian region, already mentioned, Mr. Watts devotes 170 pages to the study of this subject from many standpoints. He describes deposits of feldspar which are in all grades of decomposition approaching kaolin. Before such material can be used it is necessary to separate the kaolin clay from the semi-kaolinized feldspar or otherwise it is necessary to have a uniform mixture which can be depended upon after the proper mixture of other clays and feldspar is determined by experimentation. There is always a considerable amount of silica in one form or another in these deposits of clay and there is more or less of impurities such as oxides of magnesium, calcium and iron. There is often the mixture of minerals washed in from the surface during the time of mining, and incidental deposits and streaks of other materials which have found their way into the mass during the time of their geological formation. Some of these foreign materials may be picked out in lumps by hand. There is usually present more or less mica. Indeed, some of the mines are operated for the mica, leaving the clays only as a by-product. The mica must be removed. The methods of refining the clays differ somewhat according to the nature of the deposits, but the general plan followed is separation by difference in weight of the particles. When the kaolin is formed by the decomposition of feldspar it apparently forms a colloid of extremely small diameter. This fact is utilized to separate the fine clay from the coarser quartz sand and feldspar by floating it in water. If a mass of this material is stirred up in water the heavier particles will immediately settle to the bottom and the lighter particles can be floated off. It is by means of these settlings and flotations in water that the fine clay is separated from the coarser materials and is finally dried and thus prepared for shipment. If there exist in this mechanical mixture small particles of flint or feldspar they are of course carried over with the fine clay. Screens are used to separate the mica. In the final concentrating tank there is sometimes introduced a flocculator in the form of alum in order to hasten the settling of the very fine clay particles.

With all these possibilities of impurities arising in the process of mining, with all the different molecular forms which this material may take and all the variations which may occur from one part of a mine to another, and with the impossibility of getting any chemical analysis in general on which a practical porcelain manufacturer can depend, it will be appreciated that the difficulties in getting and maintaining the proper mixtures in a porcelain factory are very great.

32. SOME OF THE SALIENT POINTS IN THE FACTORY PROCESS

The points in which we are interested in general are those which have a direct bearing on the final product as an insulator. After an examination of the dielectric strength of porcelains from four different manufacturers, all of which use different clays, and therefore vary in their chemical content to a certain extent, it would seen that within a considerable range, the minerals, as such, have little bearing on the dielectric strength. The minerals, inregard to their ease of working and uniformity, may have considerable to do with the final product in avoiding cracks, flaws, laminations, and other like mechanical accidents of manufacture.

Certain quantities of china clay, ball clay, feldspar, and flint are ground separately to impalpable powder and are weighed out and thrown into a large tank, known as an agitator, in which there is a motor-driven paddle which constantly keeps the material mixed up. The liquid consisting of these fine particles suspended in the water, of the consistency of heavy cream, is known as " slip." There is the possibility of some slight difference in uniformity due to difference in weight of the particles, and this is the first possibility of non-homogeneous material. A porcelain manufacturer states, however, that the probabilities are comparatively slight since all the material is made fine enough to pass through a certain size sieve—100 to 200 mesh per inch.

After being mixed in the agitator tank, the slip is pumped into filter presses in which the water is forced out through canvas, leaving the fine materials deposited in the form of soft wet cakes. In this deposition there is a tendency for the coarser material to segregate from the finer materials. Since this filter press is worked under considerable hydrostatic pressure and the fibers of the canvas must finally wear out, there will be occasionally here and there a fine cotton fiber which finds its way into the mass of clay. This fiber, carbonized in the firing, will form a ready path of puncture.

The cakes of deposited raw porcelain which come from the filter press are thrown in a pile and hammered down by a large mallet. This material is then sliced off by means of a thin wire having a wooden handle at each end, and the pieces are thrown into a pug mill. Human hairs, threads, and other carbonacious substances occasionally find their way into the porcelain during this period and subsequently cause an electrical flaw.

The pug mill consists of a cylindrical receptacle about five feet high. In the center of this cylinder there is a vertical shaft from which extend horizontal arms or blades formed like the propeller of a boat. The blades cut through the plastic mass and constantly squeeze out the air and force the material downward. At the bottom is a horizontal opening, four to eight inches in diameter, out of which the soft mass is squirted by the pressure exerted by the blades above, or by an auger near the exit. It then has a consistency barely sufficient to hold its form. As this plastic mass comes from the pug mill it is cut off into cylindrical pieces by means of a fine wire. The proper manipulation of the material in the pug mill is considered of very great importance, as it is possible to leave the clay in a condition in the pug mill which will subsequently cause a sufficient defect in a porcelain part to condemn it for practical use. The pug mill is used to remix the constituent parts so that the materials will be uniformly distributed through the entire mass. To obtain this end, it is sometimes necessary to put the raw porcelain through the pug mill more than once and, as an interesting incident, it is necessary to add more water to the mass each time it goes through, to replace the loss due to heating which results from the friction of the revolving blades against the plastic mass. Before the raw porcelain is thus mixed in the pug mill it is possible to pick out spots where even inexperienced persons can recognize non-homogeneous conditions by the feel and plasticity of the soft mass.

In the usual molded process the soft plastic mass as it comes from the pug mill is formed or "jiggered" into a "blank" of the approximate shape which it is finally to have and the "blank" is then left to partially dry. It is sometimes jiggered into a plaster of Paris mold. As the moisture evaporates from the surface the material shrinks to a certain extent and since the outer surface must always be drier than the central parts there must always exist a tendency for cracks to form on the surface. This is prevented by not having the plaster mold too dry, by keeping the design dimensions within reasonable limits, usually within an inch of thickness, and by controlling the moisture content in the atmosphere of the drying room. Where a drying room is full of fresh samples the humidity of the room is high and consequently the drying will be slow. In times of slack work where a less number of pieces is drying there will be more rapid drying and consequently a greater danger of damage through shrinkage. There will be a difference due to the humidity of the seasons.

When the material becomes fairly dry it should have sufficient strength to allow it to be handled in packing it in the saggers ready for firing and, in many cases, sufficiently strong to allow of turning in a lathe. Herein comes an important factor of plasticity and coherence in choosing the ingredients of the porcelain.

33. Glazing

After the porcelain pieces have become well air-dried they are glazed. The usual glaze consists of a material essentially the same as the porcelain except that a higher percentage of flux is used, which makes the glaze melt and run over the surface at a temperature which barely vitrifies the body of the porcelain. The flux of the glaze unites with the porcelain body on the surface and forms a chemical combination which makes a gradation from pure glaze to pure porcelain.

The glaze is put on the surface by means of dipping. The fine material in water in the tank is often kept in suspension by means of a stirrer and the dry surface of the porcelain absorbs the water and thus produces a thin coating of the glaze material on the surface in a powdered form. The moisture thus introduced in the material is then allowed to dry out, and if the whole surface of the porcelain has been glazed it is necessary to scratch off the powder of the glaze where the porcelain piece will rest on the sagger or otherwise the porcelain piece after firing would be glazed solidly to the sagger. The colors of the glazes are produced by different oxides.

In other kinds of pottery there are other glazes and other methods of glazing used which have no application to any of the electrical porcelains. In some of the earthenware materials glazing is produced by throwing common salt, NaCl, onto the red-hot material. The chlorin is given off and the free sodium combines with the earthenware material and thus forms a glaze. In some work known as biscuit porcelain, used especially in art work, the porcelain is given a preliminary firing at a high temperature with no glaze on it. It is subsequently covered with a glaze requiring a much lower temperature to melt it. Such a glaze will often have a difference of expansion relative to the porcelain body and there is involved, therefore, a great tendency to check or crack, known technically as "crazing." Electrical porcelain, in general, is fired only once and glazed at that time or not at all.

34. Firing

After the clay has been thoroughly air-dried, and possibly baked to a temperature of 110 degrees to drive off all the free moisture, it is packed in saggers, which are yellowish, rough earthenware dishes, in the material of which there is a very small content of flux and therefore a much higher melting point than the porcelain parts which they contain. The usual saggers are cylindrical in form, a foot or two in diameter and high enough to accommodate the porcelain pieces. They are open at the top. These saggers containing the porcelain parts are stacked in the furnace one on top of another, making a column from the base of the furnace to the top. This column of saggers is called a bung. The furnace is completely filled with these bungs, leaving only room here and there above the many openings in the base of the kiln for the heat flames to rise as uniformly as possible through the entire mass. The usual kiln is bottle-shaped. Around its base at equal distances are eight fireplaces which feed into a radial flue running to the center with several vertical openings into the kiln.

The fires are then started, using either a good grade of coal or gas, and the temperature is gradually brought up for hours to a value in the neighborhood of 1310 to 1360 deg. cent. After reaching the maximum temperature it is usual to hold the temperature for several hours in order to let the heat soak uniformly throughout the mass of bungs. The fires are then allowed to die out and the kiln cools, the whole process taking several days, depending on the size of kiln. The fire-brick door is knocked out, the saggers are unstacked and the porcelain parts taken out and examined for flaws. The porcelain parts which pass this visual inspection are then ready for the electrical tests.

35. A Review of the Processes of Porcelain Manufacture which have to do with the Dielectric Strength of the Porcelain; the Choice of Ingredients as Affected by Firing

The firing temperature of a furnace is fixed by experience with a certain mixture of porcelain ingredients. It is assumed that each mix of this material is the same as the previous one on which the experience was obtained. Necessarily, then, whatever be the chemical contents of the bins marked china clay, ball clay, flint, and feldspar, this material should be uniform. If these materials vary in chemical composition there is no definite way of determining it until the firing is completed and all the damage is done. If the flux is too small in quantity the porcelain may be found under-fired and porous; on the other hand, if the flux is too great in quantity the porcelain parts may be over-vitrified and therefore brittle and they may even be warped entirely out of shape by becoming too soft. An important point in this regard seems to be to keep enough solid material in the form of either alumina contained in the clay or relatively large particles of flint so as to hold the body of the porcelain in form during the firing. The desire of the ceramist is to obtain a body and flux which will have a wide range of temperature between the lowest temperature which will cause a softening of the flux and the lowest temperature which will cause a warping of the porcelain due to its own weight. The initial ingredients are then of great practical importance to the ceramist in obtaining a useful article, when the firing is completed, both in form and dielectric strength. Porous porcelain will absorb moisture and will therefore have its insulating value greatly decreased. As already stated, there is always some surface on the porcelain piece which is not vitrified and it is through this surface that moisture may subsequently enter the whole body of porous porcelain. If the porcelain is over-vitrified it will be brittle, and although its dielectric strength may be excellent it is liable to damage in shipment or installation due to its fragility.

36. HOMOGENEITY OF STRUCTURE IN THE PLASTIC FORM

Assuming, then, a proper choice of the mixture, the next important step is the conditions of the pug mill. The material must be made thoroughly homogeneous when it leaves the pug mill. Otherwise there will be a separation into laminations or local spots that are not fully vitrified together. If many porcelain parts of irregular form are broken up after they have been punctured electrically laminations will frequently be found in the material. It is stated that some of these laminations really originated at the time the clay was passed through the pug mill. As the raw porcelain in flat cakes comes from the filter press it will frequently contain a layer of flint. This layer of flint lacks plasticity and if not thoroughly mixed with the ball clay in the pug mill the raw porcelain in drying will open in a lamination or crack at this surface of weak plasticity. Where the lamination is perpendicular to the lines of electric force very little weakening in the dielectric strength of the porcelain piece takes place, but where this lamination occurs at an angle or parallel to the lines of electric force the porcelain part usually lacks enough dielectric strength to make it useful.

37. Flaws Developed during the Process of Drying in Air

Occasionally it happens that changes of moisture in the atmosphere, especially in the dry season, which is the winter time in the cold countries, will cause a shelf-full of drying porcelain or a few on the end of the shelf to dry with such great rapidity as to introduce local internal mechanical strains in the body of the solidifying material. It is therefore of great value to study the rate of change of plasticity and shrinkage at the different states of drying. Bourry (Treatise on Ceramic Industries—D. Van Nostrand Co.—) shows by the curves which follow that the greatest contraction takes place in the clay body at the time it is changing from a soft plastic condition to a solid form. Subsequently, although the moisture is still considerable, the shrinkage is very much less. It is therefore during the early stages of drying that the greatest care must be taken to prevent a rapid evaporation from the surface of the porcelain. Subsequently much less care need be taken and more haste is permissible.

38. Theory of Drying

Bourry divides the drying of raw porcelain into three periods. The plastic material consists of solid particles and water. The solid particles are all small but vary greatly in dimension from the very fine particles of clay to the coarsest particles of flint. Each one of these particles is surrounded by a film of water held in position by capillary attraction. This gives a certain fluidity or ease of movement of one particle over another and is one of the factors which accounts for plasticity. In this soft condition it can be stated that there is a certain definite volume of solid material and a certain volume of water. As the drying proceeds, the film of water between particles becomes thinner and the particles approach each other, which gives the general shrinkage or contraction of the body.

When these particles come into contact there can be no further shrinkage, although there is still a considerable percentage of moisture in the mass. During this second stage when the particles are coming into contact the volume of moisture is decreasing at a greater rate than the shrinkage. It is probable that if all the particles were of exactly the same dimensions there would be a very definite cessation of shrinkage when the particles come into contact. Due to the fact that the particles vary greatly in dimensions and the surface dries faster than internal points, there is a gradual falling off of the shrinkage, while the moisture continues to decrease at about the same rate.

In the third stage the particles have all reached their minimum separation and the shrinkage entirely stops. During this third stage, however, moisture is still given off until finally all the free moisture has disappeared and there remains only the moisture of constitution in the particles themselves.

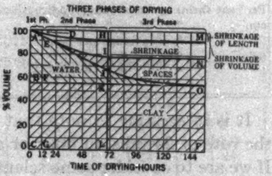


FIG. 15

Bourry's diagram of the relation of drying to volume, showing the percentage of clay, water, spaces, shrinkage of volume, and shrinkage of length.

Bourry illustrates these three phases (Fig. 15) by tests on a cylinder of clay having a length of five times the diameter. The diameter was 1.575 in. (4 cm.) and the length 7.874 in. (20 cm.). The volume of solid material in the beginning was 55 per cent and the volume of water 45 per cent. At the end of the first period, when the shrinkage and water decreased together, there was a reduction of 5 per cent in the volume which came from the loss of 5 per cent of the water, leaving 40 per cent. At this time the spaces between the particles were 0; the lineal shrinkage was 3.7 per cent or 0.74 cm.

At the end of the second stage of drying the volume of the clay was still 55 per cent, the volume of the clay and water was 67 per cent, and the volume of the water 12 per cent. The volume of the spaces between the particles was now 11 per cent. The total shrinkage was 22 per cent. The lineal shrinkage was 8 per cent.

At the end of the third period the percentage volume of water was 0. The percentage volume of the spaces between the particles had increased to 23 per cent but the total shrinkage remained as at the end of the second period, namely 22 per cent. Also the percentage lineal shrinkage remained 8 per cent. All of these relations are better shown in the accompanying table, taken from Bourry's curves which are reproduced in Fig. 15.

At the end of periods	1st	2nd	3rd
Per cent volume of clay	55.	55.	55.
" " " " " and water...........	95.	67.	67
" " " " water....................	40.	12.	0
" " " " spaces between particles.....	0	11.	23
" " " " shrinkage................	5	22.	22.
Per cent shrinkage in length.................	3.7	8.	8.
cm. " " "	0.74	1.6 cm.	
" " average per hour..........	0.06	0.027	
mils " " " "	24 mils		
" " " " minute........	0.4 "		

It is interesting to note that the lineal shrinkage decreased at the rate of 24 mils an hour or at the rate of 0.4 mil per minute. If we are to consider some scientific instrument for measuring the rate of shrinkage here is a variable factor which is available for use.

Another factor for use would be the variation in weight. For the sake of completeness Bourry's tabulated data of this test are given below.

Duration		Weight of			Shrinkage lineal Per cent	Volume of				Per cent total volume
		Clay per cent	Water			Clay per cent	Water		Spaces per cent	
Days	Hr.		per cent	per cent change			Per cent	Per cent change		
	2	75	25.0		2.1	55.1	44.9			100.0
	12	75	21.5	3.5	3.7	55.1	38.7	6.2	0.0	93.8
1	24	75	18.0	3.5	5.1	55.1	32.4	6.3	1.8	89.3
	36	75	14.5	3.5	6.5	55.1	26.1	6.3	3.3	84.5
2	48	75	11.2	3.3	7.6	55.1	20.2	5.9	6.4	81.7
	60	75	8.0	3.2	8.0	55.1	14.4	5.8	9.4	78.9
3	72	75	5.6	2.4	8.0	55.1	10.1	4.3	12.7	77.9
	84	75	3.8	1.8	8.0	55.1	6.8	3.3	16.0	77.9
4	96	75	2.5	1.3	8.0	55.1	4.5	2.3	18.3	77.9
	108	75	1.7	0.8	8.0	55.1	3.1	1.4	19.7	77.9
5	120	75	1.1	0.6	8.0	55.1	2.0	1.1	20.8	77.9
	132	75	0.7	0.4	8.0	55.1	1.3	0.7	21.5	77.9
6	144	75	0.3	0.4	8.0	55.1	0.5	0.8	22.3	77.9
	156	75	0.0	0.3	8.0	55.1	0.0	0.5	22.8	77.9

As an additional factor, the rate of drying has considerable to do with the value of the shrinkage. Two identical samples were dried at different rates. One sample was dried in one day and shrank 7.75 per cent. The other sample was dried slowly in 15 days and shrank 8.50 per cent, which is an increase of 10 per cent in the shrinkage.

The rate of drying is affected by the consistency, that is to say, by the percentage of moisture present. Bourry gives an illustration of samples of plastic porcelain in which the initial quantity of water was 10 per cent, 20 per cent and 30 per cent. The one with the highest percentage of water dried the fastest. The results are shown in the following table:

Proportion of water	10 per cent	20 per cent	30 per cent
Loss in per cent in 1 day	4%	5%	8%
Days to dry...............................	4-1/2	5-1/2	6-1/2
Ratio of days to dry.........................	1	1.22	1.44

Since the rate of evaporation is affected by the amount of moisture present, if a tool used in forming the plastic porcelain squeezes out moisture locally, mechanical strains will be introduced during drying which may cause laminations or cracks. This result may be due to the difference in content of moisture or it also may be due to a segregation of the plastic clay from the non-plastic powdered flint. The plastic clay will ooze through the solid flint and may produce locally a non-homogeneous condition. This non-homogeneous condition will affect not only the rate of drying and the plasticity but also the vitrification in the furnace when it is at its maximum temperature.

Bourry gives very little definite information regarding the content of moisture in the plaster of Paris molds. When the plaster of Paris molds are very dry the moisture is taken away from the surface of the porcelain in contact with the mold so rapidly as to cause it to check. Where the "blank" is subsequently turned down on a lathe these surface cracks are turned off.

In every case it must be understood that moisture cannot flow unless there is a different degree of moisture. Consequently the surface of the porcelain must always be drier than the interior and the problem is to keep this difference in degree of moisture to a value which will not cause cracks from unequal shrinkage. The movement of moisture from particle to particle corresponds to the transference of heat through an ordinary solid body, also to difference of potential in the electrical circuit. If projecting parts are used on the porcelain surface it is sometimes necessary to retard the evaporation from these localities where the area exposed, relative to the volume, is much greater than the same ratio for the main body of the drying porcelain.

39. FLAWS DEVELOPED DURING THE PROCESS OF DRYING AND DEHYDRATION IN THE KILN

Another critical stage, apparently, in the manufacture of porcelain, occurs in the kiln at a temperature of 400 to 500 deg. cent. At this temperature the water of composition of the clay is thrown off. The changes taking place in the green porcelain are illustrated by a study made by Messrs. G. H. Brown and E. T. Montgomery in the U. S. Bureau of Standards, published in Bulletin No. 21. Fig. 16, taken from the Bulletin, is the rectangular diagram of the loss of weight in per cent for different temperatures of firing on a North Carolina kaolin. The material was air-dried to 110 deg. before this test was started, so that probably the free moisture had been all evaporated. From a temperature of 110 to 400 deg. the loss in weight was slightly less than two per cent, but between 400 and 450 deg. the loss of weight was approximately 10 per cent and the total loss of weight up to 800 deg. was 14 per cent. From 800 to 1000 deg. no further decrease in weight took place. When we consider that the air-drying stage of a porcelain piece will usually require about three weeks and the decrease in moisture is less than occurs in the porcelain kiln it is seen that a possible damage might be done to the porcelain material during the early and apparently unimportant part of the firing. To remove from the body of a piece of porcelain 10 per cent of its weight in the form of moisture within a few hours would necessarily involve a rapid movement of moisture from particle to particle. The green porcelain is in a stage of drying in which the rate of drying may be high since there are only small changes in volume

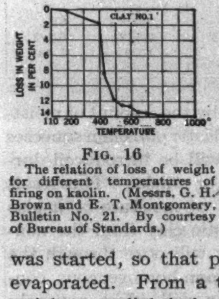


FIG. 16

The relation of loss of weight for different temperatures of firing on kaolin. (Messrs. G. H. Brown and E. T. Montgomery. Bulletin No. 21. By courtesy of Bureau of Standards.)

taking place. The spaces between particles increase somewhat, that is to say, the porosity is greater at this stage. It is possible that a considerable expansion of the material may take place during this period and if the rise in temperature is too rapid the material will be puffed and warped by the sudden changes. If the air-dried porcelain is placed directly into a hot electric furnace it will be reduced to a powder.

There is a limit to the thickness of porcelain that can be successfully fired (in general about 1.5 in.) and it may be that one of the factors which gives this limitation is the method of firing universally employed, especially the rate of change of temperature in the neighborhood of 400 deg.

The effect of time on this dehydration of the kaolin is given in Fig. 17, taken from Bulletin 21. This curve shows that at a temperature of 450 deg., most of the moisture will be thrown out in about 30 hours. At 500 deg. most of the moisture will be thrown out in five hours.

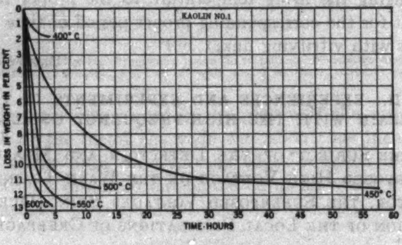


Fig. 17

The effect of duration of time on the dehydration of kaolin. (Bulletin No. 21. By courtesy of Bureau of Standards.)

40. Vitrification

Another important stage of the formation of porcelain is the time of maximum temperature. The chemical dissolutions and combinations which take place in the semi-molten condition require considerably more time than when the materials are in a molten fluid condition. Consequently a temperature of 1310 deg. held for several hours may give complete vitrification, whereas a shorter time would leave the material under-vitrified. Briefly stated, the vitrification depends not only on the temperature but also on the duration of the high temperatures. The time of cooling is usually so slow that in general this is a stage of comparatively little danger, since the porcelain has already attained the characteristic of having a very small coefficient of expansion.

41. Summary of the Important Points in the Manufacture of Porcelain for Electrical Purposes

1. Composition (chemical and molecular).
2. Keeping the ingredients uniformly mixed.
3. Keeping the ingredients uniformly plastic.
4. Keeping the mass from unequal contractions in drying.
5. Keeping the mass from unequal contractions in firing.
6. Bringing the firing temperature to the proper range and holding it for the corresponding proper period of time to fill up the pores with vitrifying flux.

PART III. EXPERIENCES AND EXPERIMENTS IN TESTING PORCELAIN WITH THE HIGH-FREQUENCY OSCILLATOR

42. On the Subject of the Detection and Measurement of Superposed High Voltage on the Wave Trains of the Oscillator, the Superposed Voltages Being Due to the Reflection of the Local Oscillations of Creepage Sparks

It was noted in two different sets of tests that a type of porcelain bushing having an average puncture potential of 85 kv. under oil may *apparently* have a higher value of puncture voltage, as represented by the setting of the sphere gap, when a creepage spark is allowed to play over the surface of the oil between the two electrodes, the porcelain bushing in this case being near the surface of the oil so that its central metallic conductor is parallel to the oil surface and therefore in a position to encourage the formation of a creepage spark. Under these conditions of creepage spark the average puncture potential of a bushing of the same type was over 100 kv., an increase of 17 per cent.

There are so many variable factors in comparing these two conditions that it is difficult to draw directly definite conclusions as to the cause of the difference.

The following is a description of the two sets of tests, after which a discussion will be given of the various factors involved.

A porcelain bushing, 13.5 in. long, and having an average thickness of 0.94 in. at the thinnest part of the corrugation, was supported horizontally on a metal rod and immersed in oil, Fig. 18. The metal rod was connected to the ground and a vertical electrode was placed in the groove of the corrugation. The width of the metal electrode was about one inch and its thickness about 3/16 in. with the edges rounded off. Both these electrodes projected out of the oil at an average distance of 12 in. apart. Consequently, when the potential was applied above a certain voltage, sparks over the surface of the oil were produced between the two electrodes. The question arises, did the creepage sparks increase the gap setting of the spheres by superposing surges on the wave trains of the oscillator? We know from much experience in testing with 60-cycle fre-

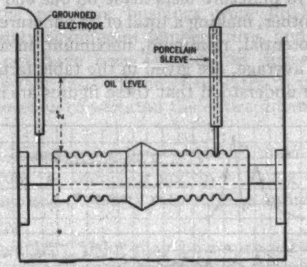


FIG. 18
One method of applying high-frequency potential to porcelain bushings under oil. The end of the electrode on the right was two in. wide and ¼ in. thick, rounded on the edges.

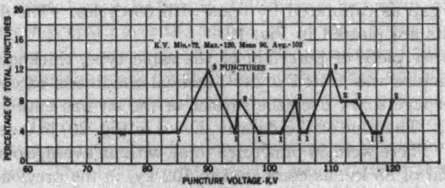


FIG. 19
Puncture voltage of porcelain bushing under oil. Representation of the percentage of punctures which took place at different impressed voltages as the voltage was gradually raised at the rate of about 5 kv. every 10 seconds. The numbers at the points represent the numbers of punctures at different spots of the same bushing.

quency that local sparks on an insulator or lightning arrester under test, will greatly increase the equivalent gap in parallel, although the voltage by ratio remains the same with or without the sparks.

There were 13 puncture tests made on one end of the bushing and 12 on the other, making a total of 25 punctures. The values of puncture potential, minimum, maximum, mean between the extremes, and average, are given in the table farther on.

It should be understood that these figures are not actual voltages, but the voltages corresponding to the gap setting of the sphere gap as calibrated by tests with 60 cycles. The data of the tests are plotted in Fig. 19.

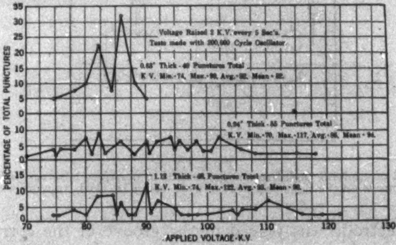


FIG. 20

Puncture of porcelain bushings under oil. Three different thicknesses are shown. Percentages of total punctures are plotted in relation to the kilovolts at puncture. Each curve represents punctures at different points on the same piece of porcelain.

Another piece of porcelain of the same type, thickness, and manufacture was tested under identical conditions except that the creepage spark over the surface of the oil was entirely prevented. The plot of the data is shown in Fig. 20, in the second curve. There were 55 punctures total, with an average puncture potential of 85 kv. as compared to 102 kv. in the previous test. This information is tabulated in the table below.

	One bushing, tests allowing creepage spark			Another bushing, tests with no creepage spark
	1st end	2nd end	Total	
No. of tests	13	12	25	55
Minimum	72	90	72	70
Maximum	114	120	120	118
Mean	93	105	96	94
Average	96	107	102	85

To forestall questions which are bound to arise the following speculations are given: So far as the data here collected are concerned, the cause of this difference may be any one of several, alone or in combination. These possible causes will be enumerated: First, the porcelain bushings were fired at different times, and possibly at different temperatures, and the porcelain material may not have been identical in dielectric strength. (As a matter of fact, tests will be given later to prove that the difference in porcelain constituted the entire difference in dielectric strength).

Second. The creepage sparks over the oil make a demand for more energy from the oscillator and in so doing the regulation drops the voltage and therefore may require an increased length of the control gap.

Third. Momentarily there may be impressed on the circuit a high voltage corresponding to the unloaded condition of the transformer. This voltage may start a new creepage spark.

Fourth. The rapid extinction of the creepage sparks may reflect local oscillations of extremely high frequency back to the sphere gap and these local oscillations may cause the sphere gap, at a certain setting, to spark over more easily, due either to a higher voltage or to a higher frequency,—or both may exist at the same time.

Fifth. Again, another factor is involved in the relative dielectric spark lag of the 0.94 in. thickness of porcelain, and the long creepage spark over the surface of the oil. If the creepage spark takes place more quickly than the puncture of the porcelain, the creepage spark by absorbing more energy and dropping the voltage may be an actual protective gap to the porcelain.

Sixth. There is also a factor which enters into this problem in the matter of time of application of voltage on the surface of the porcelain. The electrode employed has comparatively thin edges and therefore its potential gradient will be high at the surface of the porcelain. This high potential gradient, when the voltage is carried up to a value approaching the puncture potential, will begin to damage the porcelain locally at the electrode. Failure of the porcelain should therefore be a gradual growth depending upon the time of application.

If the user of the oscillator had to take into account all these complex factors it would require a rare technical skill. It will be the object of the studies which immediately and later follow, to show that complications of superposed oscillations, frequency, and so forth are usually negligible factors in testing insulators with the oscillator. The problem is thereby stripped of most of its complications, leaving a simple condition which takes care of itself automatically in the practical procedure of testing.

43. TESTS TO DETERMINE WHETHER CORONA STREAMERS AND CORONA SPARKS PRODUCE LOCAL OSCILLATIONS IN THE CIRCUIT WHICH AFFECT THE SPHERE GAP SETTING

In the previous tests of porcelain bushings the electrodes were so arranged that a spark could take place over the surface of the oil just above the bushing. With this arrangement it was possible to limit the stresses on the bushing to a local point where the upper electrode touched it, yet at the same time get a creepage spark over the surface of the oil. Ordinarily when tested in air the creepage spark over the surface of the porcelain is liable to find some weaker spot than the one where the electrode rests and thereby cause a discontinuation of the experiments by puncture.

In order to exaggerate the effects of creepage sparks, a pane of glass $\frac{1}{8}$ in. thick was used as dielectric. The electrodes consisted of two iron rods $\frac{1}{2}$ in. in diameter, with rounded ends. These electrodes were placed in the same axial line on opposite sides of the glass.

44. FIRST SET OF TESTS ON GLASS

In the first set of tests the control gap and equivalent spark gap were increased at the same time. As the impressed voltage was increased the corona streamers, mostly blue but sometimes slightly white, increased in area over the surface of the glass. At the maximum voltage obtainable, namely 45 kv. by spark gap with a setting of 11.1 kv. on the control gap, the radius of the corona was $5\frac{3}{4}$ in., giving a total area on each side of the glass plate of 104 square inches. The following series of readings was taken:

Control Gap	Spark Gap
1.8 kv.	32 kv.
3.0 "	34 "
4.6 "	36 "
6.7 "	38 "
11.0 "	40 "

As an explanation of why the voltage generated by the oscillator is apparently so very limited we must look to two different causes. First, the corona is equivalent to an increase in capacitance. Second, the corona absorbs energy. Either of these causes will limit the potential of the oscillator by overloading it.

In order to determine the effect of capacitance, tin-foil plates, 7 by 9 in. (63 sq. in.), were used as electrodes. As a result the maximum voltage obtained was reduced from 45 kv. as given in the previous test, to 28 kv. Even at 28 kv. there was a corona of 1½ in. visible in daylight surrounding the tin-foil plates. This made a total area covered by plate and corona of 10 by 12 in. (120 sq. in.). During this test the control gap was set on 11.5 kv. With the electrodes alone the area was 104 sq. in. which was increased to 120 sq. in. with the plate and corona together. This increase of 16 per cent in area reduced the voltage by 37, per cent. The area of corona around the metal plates was 57 sq. in. which is a little less than half of the corona area in the previous case. It would appear from these figures that the capacitance was a large factor in reducing the voltage at the terminals of the oscillation transformer.

Capacitance of glass plate ⅛ in. (0.322 cm.) thick and an area of 104 sq. in. (670 sq. cm.) is 1.1 milli-microfarads (10^{-9} farads).

At 300,000 cycles and 45 kv. this capacitance of 1.1×10^{-9} farad gives a momentary load of about 29 amperes or 1170 kv-a.

This capacitance of 1.1 milli-microfarads is equivalent to the capacitance of thirty suspension type insulators in parallel, which is three to six times full load for this oscillator.

45. Equivalent Spark Gap of Corona on a Glass Plate

The equivalent spark gap of corona on glass plates is dependent upon the voltage applied. Two tests of a slightly different nature follow. In the first one, the spark gap was set permanently on 37 kv. and the control gap was gradually increased. With the control-gap setting of 3.2, a spark was formed around the edge of the plate which was 4½ in. away from the electrode, making a total length of spark of 9 in. No discharges took place over the spark gap for this low setting of the control gap.

At a setting of 4 kv. of the control gap there was one discharge over the spark gap in seven total.

At 5 kv. setting of the control gap there were four sparks over the spark gap to ten total.

At six kv. setting of the control gap there was about equality between the spark gap and the spark around the glass plate, that is to say, five out of ten total.

At seven kv. setting of the control gap the sparks over the spark gap increased to seven in ten impulses.

At eight kv. setting the sparks over the spark gap increased to eight in ten impulses.

At 8.5 kv. setting of the control gap there were nine discharges over the spark gap out of a total of ten impulses.

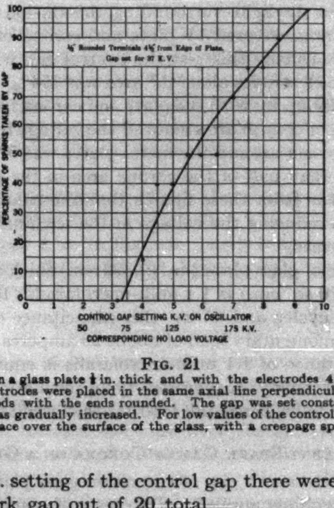


FIG. 21

Arc-over tests on a glass plate ⅛ in. thick and with the electrodes 4½ in. from the edge of the plate. Electrodes were placed in the same axial line perpendicular to the plate, consisting of ½i-n. rods with the ends rounded. The gap was set constantly on 37 kv. and the control gap was gradually increased. For low values of the control gap, 3.2 kv. all the discharges took place over the surface of the glass, with a creepage spark of total length of 9 in.

At nine kv. setting of the control gap there were 19 discharges over the spark gap out of 20 total.

At 9.5 kv. setting of the control gap there were 40 discharges of the spark gap out of a total of 40, but at a setting of ten kv. on the control gap one discharge took place over the glass plate, making a record of 39 over the spark gap to 40 total.

At a control gap setting of 10.5 kv. there were 100 successive discharges over the spark gap out of a total of 100 impulses, there being very slight tendency to spark on the glass plates.

In this set of tests it is seen that the equivalent spark gap of electrodes separated by a thin glass plate depends upon the value of the applied potential, just as has been shown in tests on lightning arresters using Leyden jars charged from the static machine.

The change in the equivalent spark gap is shown diagrammatically in Fig. 21.

46. THE EQUIVALENT SPARK GAP WITH THE CONTROL GAP REMAINING CONSTANT

In the next set of tests the control gap was set on 3.5 kv., which was just sufficient to cause 4½ in. radius of corona, and a spark around the edge of the glass plate. It was necessary to reduce the spark gap from 37 kv. setting to 32 kv. setting in order to take the spark away from the glass plate. It should be recalled that at high control-gap setting the spark gap set even on 37 kv. took all the discharge away from the glass plate.

By increasing the control gap setting to four kv. and with a setting of 32 kv. on the spark gap, it was possible to take away the discharge from the glass plate and keep it in the spark gap. When the spark gap was increased two kv. to 34 kv. there were 32 discharges over the spark gap out of a total of 40, leaving eight discharges over the glass plate.

With the control gap setting of 10.5 kv. it was necessary to elongate the spark gap to 44 kv. before the discharges would all take place over the glass plate.

In none of these tests do we find the solution of the problem of the effect of the oscillation set up by the corona streamers and corona sparks. Therefore the next set of tests was planned to throw some light on this subject.

47. THE PUNCTURE VOLTAGE OF A GLASS PLATE WITH A DROP OF OIL AROUND THE ELECTRODES

The same electrodes were used and a glass plate lying horizontally had a few drops of oil placed around the upper electrode. The main gap of the oscillator was then closed momentarily a number of times with control gaps ranging from one kv. up to 2.5 kv. The spark gap voltages corresponding were from 32 kv. up to 40 kv. After the eighth brief application of potential with a setting of 2.5 kv. on the control gap and 40 kv. on the spark gap the glass was punctured. This experience gives a very definite clue to theimmunity from puncture in the previous test. It should be recalled that the control gap setting was increased to 11.1 kv. and the spark gap to 45 kv. without causing a puncture of the glass. We now applied less voltage and very quickly got a puncture. The distance of the electrode from the edge of the glass in this last case was only 1.3 in. and occasionally sparks would break through or over the surface film of oil and spark around this short width of glass.

The obvious explanation of this phenomenon of puncture of glass at lower voltage than it had previously withstood is in the difference in concentration of the electrostatic field. Without the film of oil the voltage gradient at the electrode can rise only to a value which will start the corona discharge in air and any further increase in the voltage simply increases the area covered by the corona, which, in effect, increases the area of the plate and gives a better distribution of the electric field over the plate. On the other hand, when the oil is used, the corona streamers are to a very great extent restricted and the potential is concentrated locally and causes a disruptive spark to puncture the glass.

While the variations in the equivalent spark gap involved a complicated study of dielectric spark lags, the actual use of the oscillator to measure these different conditions is very simple. We must assume in each case that even if the spark gap does not measure the actual voltage it does measure always the tendency to spark, which is the condition in the circuit against which it is desirable to protect. In testing porcelain bushings in air the same effect will take place as shown in the tests on glass, in that the corona at the edges of the electrodes will decrease the effect of the sharp edges of the electrodes. In testing thin pieces of porcelain in air many new points of the porcelain are reached by the spreading of the corona streamers and there will be added the additional factor of puncture through local weaknesses in the porcelain. The porcelain is not nearly as homogeneous as glass. The wave trains generated are of very high frequency and the superimposed oscillations from local sparks, while higher in frequency, are, comparatively speaking, not much higher. As a result the spark gap is not affected very much. In other words, the change of frequency and wave front from 60 cycles to say a million cycles is enormous as compared to the change of frequency and wave front from the oscillator to that of the local oscillations. The first ratio is of the order of 17,000 and the second of the the order of 3. Herein lies the simplicity of testing with the oscillator.

In testing porcelain under oil one must take into account the maximum voltage gradient which can be applied at the contact point between the electrode and surface of the porcelain without damaging the porcelain. This value of voltage gradient is readily determined experimentally for any particular shape of electrode that it is desired to use. Such tests will be given further on.

48. Further Studies of Puncture Potential of Porcelain under Oil by the Use of the Oscillator

Three thicknesses, namely 0.63 in., 0.94 in., and 1.12 in., were tested and recorded. The test pieces were corrugated porcelain bushings of the general form shown in Fig. 18. In Fig. 20 three curves are shown of tests on the three thicknesses. The three pieces of porcelain were each punctured a number of times. By conducting many tests on one piece of porcelain it is thus possible to keep the factor of quality of the porcelain constant. The three curves are entirely independent. The method of test was to gradually raise the potential two kv. every five seconds until puncture occurred. In plotting these data the kilovolts at puncture are taken as the abcissas and the percentage of the total number of punctures at the different voltages as the ordinates. The upper curve is the result of 40 punctures total, all on one test piece. The minimum puncture potential was 74 kv. There were two punctures at this voltage, which is 5 per cent of 40 total punctures. Percentage is used instead of the actual number of punctures in these curves so that comparisons can be made between the three different thicknesses tested. There were only two places tested that withstood 90 kv., the maximum value. This is also shown as 5 per cent on the upper curve. Attention is directed to the peculiar low point at 84 kv., as it will be shown in a different way in another diagram later. It may or may not have any special significance. Attention should also be directed to the small range of puncture potential for this thickness of 0.63 in. Most of the punctures occurred between 80 and 88 kv. These general relations may be interpreted from a tabulation of the maximum, minimum, average, and mean between the extreme values as printed on the curves. The ratio of the minimum to the maximum is 82 per cent and the mean and average values are identical, showing general symmetry in the results.

The second curve (0.94 in. thick) is the result of a total of 55 punctures taken on one bushing. This greater thickness shows a wide range of puncture voltage. The minimum puncture voltage of 70 kv. was even less than the thinner test piece. The maximum puncture voltage was 118 kv. but there was only one spot that withstood this potential. For this greater thickness of porcelain there is no definite puncture voltage as in the previous case. The ratio of the minimum to the maximum is 60 per cent, which is 22 per cent below the range of the thinner porcelain just given above.

In the third curve the thickness was 1.12 in., and a total of 48 punctures was made on the porcelain piece. Here again the puncture voltage is spread over a wide range with no definite point of failure. Apparently in both of these thicker pieces the conditions of manufacture or test of the porcelain were such as to give a wide range of dielectric strength. The ratio of the minimum spark potential in this case was also 60 per cent. In the early part of the work it was endeavored to get as many punctures as possible on one sample. In so doing it was found that the cracks from one puncture would occasionally carry into the spot where the successive test potential was applied and this spot would thereby be weakened. As soon as this fact was established greater distances were made between puncture points. To further insure that the cracks did not carry from one puncture hole to the next, further precautions were taken. The punctures were filled with red stain and then thoroughly dried, the porcelains were then broken into pieces and where the red stain showed that a crack had carried from one punctured point to another the second reading was thrown out.

49. A REPLOT OF THE DATA OF FIG. 20 TO SHOW TENTATIVELY POSSIBLE NATURAL GRADATIONS OF FLAWS

In Fig. 20 the percentage of the total number of punctures at each value of kilovoltage applied was given. In Fig. 22 the values of punctures are summed up from the lowest voltage to the highest voltage. Both curves 1 and 2 show a peculiar shoulder at 82 kv. All the curves show a bend at the highest values. Tentatively, we may interpret these curves as follows: It is conceivable that there is a certain class of flaws which are developed between 70 kv. and 82 kv. Above this value we get into the condition of the normal strength of the porcelain which requires a considerable increase above 82 kv. before the number of failures again increases rapidly. In the case of curve 1 it required 85 kv. to increase the percentage suddenly from 53 to 85. In curve 2 the range was wider, being between 90 kv. and 100 kv. In the third grade of the dielectric strength given by the porcelain there are those local spots which approach perfection in the homogeneity of the porcelain material. Therefore the high-voltage strains which are at the limit of dielectric strength do not develop into a puncture so easily. As already stated, this analysis is only tentative, and even if it is true for this particular grade of porcelain it may not apply in the same way to a different mixture of material. We have found, however, that there have been in nearly every case fairly definite degrees of flaws which can be developed in rather definite ranges of potential. To illustrate this idea, the grades might be divided as follows: First, accidental cracks or laminations which are at more or less of an angle to the surface of the porcelain and which therefore decrease the puncture length through the porcelain. In the second grade would be those flaws of the nature of "blebs" or closed bubbles, also open pores. In the third grade there exists the highest degree of homogeneity with very slight differences in dielectric strength from particle to particle as we pass from surface to surface.

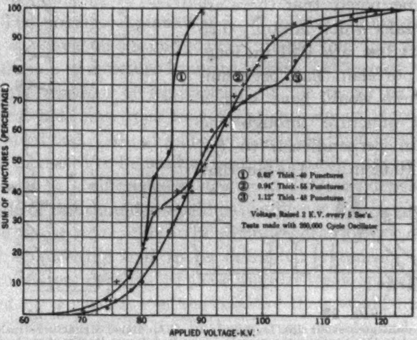


FIG. 22

A replot of the puncture tests of Fig. 20. The kilovolts of puncture versus the sum of punctures. The shoulders on the curves may represent a different grade or kind of flaw in the porcelain.

50. TESTS WITH THE ELECTRODE PLACED SUCCESSIVELY IN THE VALLEY OF EVERY ADJACENT CORRUGATION IN THE SURFACE OF THE BUSHING. THE RESULTS SHOW THE INTERNAL MECHANICAL STRAINS DUE TO SHRINKAGE

In the records of the tests shown in Fig. 19 the upper electrode was always moved a distance of two corrugations away from the previous test. In the earlier tests the electrode was moved into the adjacent corrugation. In so doing some interesting conditions relative to internal strains were disclosed. Fig. 23 shows one of several punctures which took place in the porcelain. It will be noted that there are two streaks which are only 0.25 in. apart but are 0.81 in. long. If the porcelain had been uniform there would have been a straight puncture through the porcelain perpendicular to the surface (0.62 in.). The fact that there are two punctures about 0.8 in. long, side by side, following parallel paths separated by only one-quarter inch indicates that there were mechanical strains in the porcelain, placed there during the manufacture, which caused more or less of a cleavage or a line of weakness. This porcelain was jiggered into the form of a long, smooth tube while it was in a plastic condition. After partial drying sufficient to give it enough tenacity to hold together, it was placed on a lathe and the grooves or corrugations turned into the surface of the "blank." The material was then allowed to complete its drying. Probably during this second process of drying these laminal strains were introduced. There is every reason to believe that the

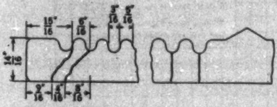


FIG. 23

Parallel puncture streaks close together as compared to the length of the streak. This phenomenon shows latent weakness in the porcelain at the end of the bushing, which seems to be due to the process of air drying.

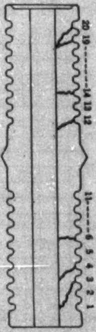


FIG. 24

A number of puncture streaks are shown at different lengths of the bushing similar to those of Fig. 23. It should be noted that all the puncture streaks at the ends and at the middle are in a downward direction, which seems to indicate the effects of air drying in causing latent cleavage surfaces in the porcelain.

lamination is not due to a layer of flint, because in the working of the soft clay there is no opportunity to cause layers systematically in the direction shown by the direction of the punctures.

In Fig. 24 are shown the paths of puncture of another porcelain bushing at several points along its length which would tend still further to confirm the belief that the cracks were due to air-drying rather than to lack of homogeneity of mixture or shrinkage in firing. The lines drawn from the grooves to the inside surface of the porcelain bushing show that at the ends and at the middle the direction of the puncture is at an angle from the radial direction and all in a parallel direction. Punctures at other points than at the ends or the middle are radial punctures. The possible explanation is as follows: This porcelain bushing was stood on one end to dry. It was therefore restricted in its radiation of moisture from the surface at the base and was given extra freedom of evaporation at the upper part where the central hole was open to a slight movement of the air in the neighborhood. About half-way along the bushing the thickness was increased to be used as a support, and at this point also there would be a difference in drying at different depths. The under side of this shoulder would naturally get more evaporation than the upper side. Since the thickness was greater, a greater amount of moisture had to be extracted, requiring a longer time for different depths. If these angular weak spots had been produced by a variation in the mixture they would have been more or less uniform in the bushing from end to end. If the angular weaknesses were due to firing in the kiln there would seem to be no reason for the peculiar distribution at the top and bottom, although naturally the thicker part of the bushing at the midway point would come in for inequalities of contraction. As a matter of observation, two small surface cracks were noted on the inside of the bushing at the thickest point but these cracks did not show sufficient weakness to divert the puncture discharge from its path, which, by the way, ended about ¼ in. from the surface crack.

51. Faults in the Skirts of Suspension Insulators

When the upper side of a skirt of an insulator is covered by tin-foil and the insulator inverted in a bath of oil, localized potentials can be applied by means of a small electrode resting in one of the corrugations or valleys between adjacent petticoats. In a number of test samples a very uniform homogeneous porcelain material was found. This was indicated by punctures directly between electrodes from surface to surface of the porcelain. Occasionally, however, conditions of internal mechanical strain were revealed by the fact that the puncture took place at an angle to a perpendicular line between surfaces and sometimes traversed a distance nearly twice as great as the thickness of the porcelain. The direction of the puncture was indicated subsequently when the porcelain was broken up with a hammer or by squeezing it in a vise. Fig. 25 shows a sketch of two different types of punctures that were found.

In a number of punctures which occurred in the heads of pin-type insulators a careful examination was made by staining and breaking up the porcelain by hammer blows. A characteristic puncture streak is shown in Fig. 26. These samples were shown to a porcelain manufacturer, who immediately set the cause of the trouble to an improper use of the tool used in forming the thread on the inner surface of the porcelain. With the information already given, one may attribute the fault to insufficient plasticity, which may have been due to lack of water, lack of enough ball clay, or too large particles of flint. It is easy to conceive of the more plastic clay being squeezed out from under the tool, leaving the material directly under the tool of a different consistency from the rest of the body of the porcelain. From this difference in body, weaknesses may be caused, either in the rate of drying or in the vitrification, due to the improper proportioning of the ingredients in this locality. In one case there was a perceptible surface crack in the porcelain which was the beginning of a puncture streak. In this case one may tentatively infer that the damage was initially done in drying and might have been found by the application of oil to the green porcelain.

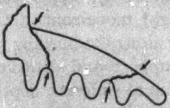


FIG. 25

Directions of puncture in a skirt of a porcelain insulator where the discharge takes a path much longer than the shortest distance between surfaces. This indicates a weakness in dielectric strength due to shrinkage strains.

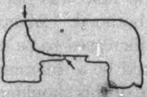


FIG. 26

Direction of puncture in the head of a pin-type insulator, showing a line of weakness due primarily, probably, to an improper manipulation of a forming tool, while the porcelain was in a plastic condition. All paths of puncture which do not take the shortest distance indicate a line of weakness in the porcelain.

In general, one may conclude that porcelain which does not puncture through the shortest distance is non-homogeneous.

52. The Growth of Corona on Insulators

The growth of corona around the electrodes and on different parts of the insulators has been successfully used as a basis of design. The oscillator with its high frequency is well adapted to bring out the characteristics of design by this method. Some tests are given in the following table to illustrate the characteristics as disclosed by the oscillator. The tests were invariably made in the dark to be able to note the first visible formation of corona.

Suspension type insulator No. 1	Kv.	Per cent of spark-over
Spark-over voltage	86	100%
Brush discharge from pins	33	38%
" " around 1st inner petticoat	47	55%
" " at cap	47	55%
" " around 2nd petticoat	74	86%

It was found impossible to brush discharge over the third petticoat without a spark-over on the insulator.

Suspension type insulator No. 2	Kv.	Per cent of spark-over
Spark-over voltage	82	100%
Brush discharge at pin	42	51%
" " over inner petticoat	48	59%
" " 2nd petticoat	59	72%
" " 0.75 in. long around cap	59	72%
" " over 3rd petticoat	72	88%
" " " 4th "	74	90%

In studying the growth of corona on the pin-type insulators, eight different samples were used. In the points of Fig. 27 the appearance of the corona in per cent of the spark-over voltage is plotted as ordinates and the kilovolts of spark-over voltage as abcissas, the points corresponding to the initial formation of corona, which invariably took place around the pin. A considerable variation in the distribution of potential is evident from the wide variation between the limiting curves as shown in Fig. 25. The variation is from 30 per cent for the high-voltage insulators, to 76 per cent for one of the best conditions of the lower-voltage insulators. Naturally the higher the spark-over voltage of the insulator the lower the percentage, because the corona depends upon the potential gradient. The potential gradient which produces corona on the pin does not differ very widely for the different types of pins and insulators.

SIGNIFICANCE OF THESE TESTS

The significance which may be drawn from tests of corona are too complex to be considered in a paragraph. They are valuable to the designer, but several points of design must be taken into account in each particular insulator. From some points of view the ideal design of an insulator would be one producing no corona until the arc-over voltage of the insulator was reached. From a practical point of view the laboratory test, unless made under the same conditions as found in the operation of the insulator, does not necessarily give the best design. For example, if an insulator is to be designed for a very dusty country or where soot and smoke will be deposited on the surface of the porcelain the conditions call for extra long surfaces for creepage. If such an insulator in a clean condition is tested in the laboratory for the appearance of corona, the corona will appear at a comparatively small fraction of the arc-over voltage. Yet if this insulator is thoroughly coated with a semi-conductor, as would occur in practise, it is quite probable that the apparently faulty design would be far better than one with shorter skirts which in the laboratory test in a clean condition gives a higher percentage of voltage for the appearance of corona. In brief, one must take into account the use of the insulator and reproduce the operating conditions, as far as possible.

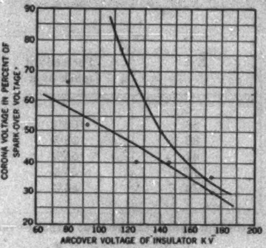


FIG. 27

The first appearance of corona on pin-type insulators, using the oscillator as a source of power. Arc-over voltage of the insulator versus the percentage of arc-over voltage at which the first corona appears on the pin. The two curves show the wide range of variation which can be found in insulators on the market at the present time.

53. PERCENTAGE OF FAILURE AS A CRITERION OF REJECTION OF INSULATORS

This would seem to be a very good rule but it may not be desirable to apply it blindly. The full significance of the tests is not yet evident. In considering the failure of insulators we must take into account the nature of the weakness. Weakness from under-firing porcelain may be more serious than weakness from over-firing. Under-fired porcelain is liable to be uniformly weak all the way through. Over-fired porcelain is liable to be weak in local spots such as cracks.

To illustrate this point, examples are taken from a number of endurance runs that were made on insulators which by examination showed thorough vitrification and a tendency to the side of over-firing.

Type X. Of three insulators, one failed in one min. (33 per cent); two were not punctured in 1 hour of test.

Type Y. Of eight insulators, three failed in one min. (37 per cent); five were not punctured in 1 hour of test.

Type Z. Of three insulators, none failed in one min. (0 per cent); all withstood 1 hour.

Type D. Of three insulators, none failed in one min. (0 per cent); all withstood 1 hour.

The experience with types X and Y in the above tabulation, although limited, would indicate that some caution should be taken in the rejection of insulators. It may even be that a high percentage of loss may be a good criterion of choice under certain conditions of over-firing. A hypothetical case will be given for illustration: The temperatures in the different parts of a kiln and the time of application of the vitrifying temperature must necessarily vary. The intensely hot flames enter at certain points and the partially cooled flames leave at other points. Both of these places cannot be at exactly the same temperature. Even assuming a final negligible difference of temperature, the porcelain nearest the entering flame must be at a vitrifying temperature somewhat longer than the porcelain near the flues. The cracks in such over-fired porcelain produce dielectric weakness and the insulators are therefore easily detected when tested, and rejected.

We may deduce that a considerable percentage of over-fired porcelain may indicate that the rest of the kiln-ful is perfectly fired. On the other hand, a temperature that will just properly vitrify the hottest spots in the furnace may leave the larger percentage of insulators at a low grade of vitrification. Their dielectric strength may be barely sufficient to pass the usual test and therefore from a standpoint of dielectric strength they are inferior insulators to the hypothetical lot that was rejected on the basis of 3 per cent failure. It is intended here only to point out that more must be known of the intimate history of a porcelain insulator to judge its worth on the basis of a percentage rejection. Intrinsic mechanical strains, layers of flint, relative conditions and rapidity of drying of a batch of insulators, rate of firing, etc., must be known to give proper weight to the basis of rejection by percentage failure.

54. Welding up the Puncture Holes in Porcelain by the Application of High-Frequency Wave Trains

Under certain conditions of puncture it has been found practicable to repeatedly puncture and weld up the puncture holes in porcelain. This may not be entirely unknown in tests with 60 cycles, although no such experience has been had by the author. There seem to be certain requirements to successfully weld up the holes without failure. The best results were obtained by Mr. Cermak in the tests of large porcelain cups which were made up of several different kinds of clay but all fired at the same time. These cups were partially filled with water which acted as one electrode and the other electrode was a wire wrapped around the outside. The punctures noted never took place directly under the wire and therefore no copper vapor was carried directly into the puncture hole. Since the other electrode was water, no metallic vapor could be obtained from this source. The time of application was varied considerably, but three seconds, on an average, would give good results. The punctured spots in this porcelain appeared as small beads of clear glass which actually had greater dielectric strength than the porcelain elsewhere, as no welded punctures were repunctured by a second application of potential. No doubt the content of feldspar in the porcelain will have an effect on ease of formation of glass or glaze in the punctured holes.

In other porcelain in which different ingredients were used and which seemed to be less homogeneous, cracks were caused which of course could not be welded up by the high-frequency arc. It is very probable that welding up of punctured holes by 60-cycle tests is not common because the punctures are more liable to take place directly between the electrodes and therefore become filled with metallic vapor, which leaves the melted porcelain in the path of the arc of weak dielectric strength. The use of the high frequency produces widely extended corona and thereby picks out flaws or weaknesses which are frequently some distance away from the electrodes, and thereby avoids the deposit of metallic vapor in the punctured holes. When punctures are made under oil there have been no cases of welding up of the punctured holes, due probably to the carbonization of the oil which is always found in the punctured streak.

55. COMPARATIVE PUNCTURE VOLTAGES OF PORCELAIN AND GLASS. PORCELAIN PIECES OF DIFFERENT THICKNESSES WERE USED, BUT THE GLASS WAS BUILT UP OF PANES PILED ONE ON TOP OF THE OTHER

The results of these tests are shown in Fig. 28. Curve 1 was made taking puncture potential on glass of increasing thicknesses.

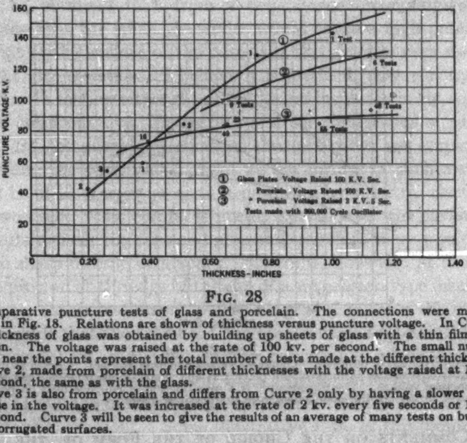


FIG. 28

Comparative puncture tests of glass and porcelain. The connections were made as shown in Fig. 18. Relations are shown of thickness versus puncture voltage. In Curve 1, the thickness of glass was obtained by building up sheets of glass with a thin film of oil between. The voltage was raised at the rate of 100 kv. per second. The small numbers placed near the points represent the total number of tests made at the different thicknesses.

Curve 2, made from porcelain of different thicknesses with the voltage raised at 100 kv. per second, the same as with the glass.

Curve 3 is also from porcelain and differs from Curve 2 only by having a slower rate of increase in the voltage. It was increased at the rate of 2 kv. every five seconds or 1/5 kv. per second. Curve 3 will be seen to give the results of an average of many tests on bushings with corrugated surfaces.

Each individual thickness of the glass was 1/16 in. and each piece of glass was immersed in oil before it was pressed against the adjacent sheet, which of course left a thin film of oil between the plates of glass. The curve shows an almost direct increase of puncture potential with an increase of thickness.

Curve 2 has only two points—one the average of six tests at 1.2 in. thickness and the other an average of nine tests at 0.62 in. thick. The tests which gave the data for curve 2 had a more rapid rise in the testing potential than the tests of curve 3. The porcelain also differed. The higher puncture potential may be credited to both of these conditions, namely, different porcelain and more rapid increase of testing potential.

The points of curve 3 are the average of 182 tests total and therefore may be considered a fair average of the porcelain which we had at hand. An important result shown by this curve is that increase in thickness of porcelain from 0.4 in. to three times as much or 1.2 in. gives an increase in puncture potential only from 74 kv. to 91 kv., which is 13 per cent. Three hundred per cent increase in thickness gives 13 per cent increase in puncture potential. Although this general condition of increasing the thickness without increasing the puncture potential is known, the small percentage of gain from an increase in thickness may be new to many.

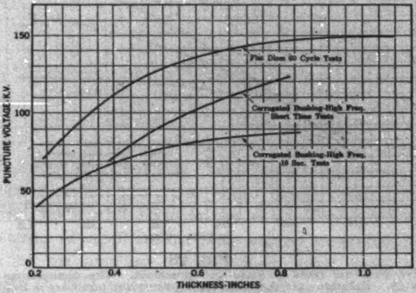


FIG. 29

Puncture voltage of porcelain. Thickness versus puncture voltage. Curves to illustrate the effects of irregular surfaces of the porcelains and shape of electrode as they influence the puncture voltage. The upper curve is a reproduction of 60-cycle tests on flat disks. The lower curves are the same as given in the previous figure.

56. COMMENTS ON THE CHOICE OF THE FORM OF THE TEST PIECES OF PORCELAIN

It has been the custom of previous investigators on porcelain to have made up in the porcelain factory plain disks of varying thickness on which the puncture potential tests were made. These plain disks of porcelain involve the easiest conditions of manufacture, both the drying and the firing being possible with a minimum resultant strain from shrinkage in the body of the porcelain. Consequently the puncture potential shown by these investigators is necessarily very much higher than shown in either curves 2 or 3 of Fig. 28. Such a curve taken at 60 cycles impressed is shown in Fig. 29, taken from results published by W.

F. Fellenberg, together with our average curve of Fig. 28. Any careful designer would take a factor of safety on the values obtained from the tests of such disks which would bring the working values even less than curve 3. The form of the porcelain part is a very important factor in the resultant dielectric strength and therefore it seems permissible to make tests on the actual porcelain parts, irregular as they may be. In order to decrease the cost of such tests, comparatively small electrodes were used, a copper strip 0.12 in. thick and 2 in. wide, rounded at the surfaces that come in contact with the porcelain, and these electrodes were moved from point to point on the porcelain part tested. By getting a great number of tests a much better average value could be obtained than from a dependence on a single test. Knowing that the small electrodes would cause a high potential gradient at the surface of the porcelain, this practise may well be brought into question. I believe it is justified, however, by the fact that in testing either a bushing or an insulator in air, corona sparks creep out over the surface and the dimensions of such a spark are comparable to that of the electrodes we employed. Therefore, the potential gradient at the surface of such a spark might be at least as great as that produced by the strip electrode that we used. The corona is evenly spread over the surface of an insulator near the caps and pins and therefore there would not be the sharp outline of a spark. There is, however, at the end of the pin and at the edge of the cap of a suspension type insulator the same concentration of potential gradients. On the whole, we conclude that the use of the narrow electrode for testing under oil up to 90 kv. is justifiable in the condition in which it is used and gives reliable results. For higher voltages the time of application of voltage must be made very short to limit local damage by potential gradient. Some illustrative tests of this point are given later.

57. THE RELATION OF PUNCTURE VOLTAGE TO THICKNESS OF PORCELAIN FOR DIFFERENT MIXES AND FIRINGS

There are three curves given in Fig. 30 showing the puncture potential of three different mixes of porcelain. The upper curve and the lower curve of the three are the puncture potentials taken on suspension type insulators and the middle curve on corrugated bushings. Therefore there exists a difference in form as well as a difference in material. The results show that there is no very wide variation between the different mixes of clay, although the color varied from a pure or bluish white to a light yellow. The porcelain which gives the lowest puncture voltage in the curves of Fig. 30 had previously given in other samples tested through the head even better dielectric strength than the samples which gave the data for the upper curve. The weakness may be attributed to the shrinkage strains coming from the presence of the petticoats on the skirt where the voltage was applied. So far as the study has been carried, it would seem that the different manufacturers of porcelain have their ups and downs of luck, and while one mix will be found high in dielectric strength at one time due to having the several factors of porcelain manufacture combined under favorable conditions, they will have other periods when poor combinations will take place and the porcelain will run a little lower in dielectric strength. It would seem that "eternal vigilance" is the price of obtaining a uniformly good product. In making designs of porcelain it is essential to use the puncture potential corresponding to the minimum average that a porcelain factory can produce.

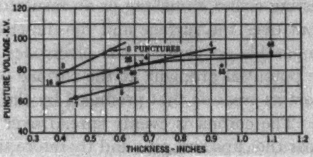


Fig. 30

A comparison of the average puncture potentials of a number of different mixes of porcelain. All tests were made on irregular surfaces. The numbers at the points represent the total number of tests made for each thickness.

58. The Technique of Development of Faults and Punctures in Porcelain and Methods of Examination

When porcelain punctures, the current may cause a single streak or it may cause a crack and, if so, the discharge usually flattens out in the crack, dividing into several paths. If the puncture occurs under oil the current will usually carry oil with it, which is carbonized in the heat of vapor of the electrodes, and both together produce a black streak which is easily seen after the porcelain is broken into pieces. The marking depends somewhat on the length of time the discharge is allowed to play through the puncture.

After the porcelain is broken up the hammer blows or pressure which is used to break it up will produce cleavage surfaces and cracks which did not exist in the porcelain before it was smashed. It is important to determine what cracks existed before the electrical test was made, what cracks were produced by the electrical test, and their extent, and what closed laminations existed in the porcelain. These three faults should be differentiated from the cracks resulting from the mechanical destruction of the porcelain piece. Otherwise stated: after a piece of porcelain is smashed to pieces it is in general impossible without a preliminary stain to detect the cause of the different cracks which appear.

The following technique has been used to advantage in the examination of the porcelains and in most cases has indicated the nature of the fault. In many cases the cause of the fault has been traced to a particular condition of manufacture which needs to be improved. In beginning the tests of a piece of porcelain, then, the first step is to determine the presence of accidental flaws so far as possible. Soaking in eosin stain or aniline violet dissolved in alcohol, under vacuum, allows the penetration of the stain into the open air-pockets and laminations. A dark stain may be used for this purpose. The stain is then washed off the surface of the insulator. Frequently the cracks will be shown up by the streaks where the stain has soaked into them and will not wash off. The insulator is then dried and punctured under oil. It is removed from the oil and the oil is washed out with gasoline or some other solvent of oil. The insulator is then thoroughly dried at a temperature above 100 deg. It is then immersed in red aniline stain (alcohol solution) and placed under a vacuum. The red stain will penetrate most of the holes and cracks that are opened up by the punctures. In removing the insulator from the stain it is wiped off, and washed off and dried, to prevent discoloration later in handling the broken pieces. The porcelain is then broken up. The original cracks are shown by the dark stain with a layer of red stain on top and the developed cracks are shown by the red stain alone. In some cases it is found difficult or impossible to remove the oil from a crack and this oil will be found on the surface of the crack as an indicator that the crack was produced by the discharge. Any surface of a broken piece which shows neither stain nor oil, it is natural to infer, is produced by the mechanical strains of the hammer or vise. The alcohol solutions are far more penetrating than solutions in water, such as ink.

59. CLOSED PORES AND BUBBLES, KNOWN AS "BLEBS"

In the glazes on electrical porcelain, so far examined under a microscope, all have contained bubbles which have the same appearance as the familiar bubbles in common glass. A magnifying glass is sufficient to bring these to view but a magnifying power of 50 is desirable for careful examination. A magnifying power of 250 diameters usually obscures them because the focus is of such short range that only a part of a bubble can be seen with one setting of the lenses. They are more easily seen and studied in colored glazes than in the clear glaze. The size of the bubble and the number of them differ in the glazes from different manufacturers—in fact they differ in number on the same piece of porcelain. On ridges the glaze is liable to run thin; in the valleys of corrugations it is much thicker and as many as three bubbles can be found at the same position of the microscope at different depths in the glass. These bubbles are apparently formed by a boiling of the glaze at the temperature of 1310 deg. cent.

No significance has been attributed to them so far, but our very recent experiments on the beginning of failure, as given later under tests with potential gradient, indicate that under certain conditions these bubbles may play a not unimportant part in the failure of the porcelain back of them.

The bubbles being formed at high temperature, the gas they contain must be at a partial vacuum and therefore easy to ionize by the application of voltage.

When these blebs appear in the body of the porcelain it is natural to infer that either too much feldspar or other flux has been used, or the temperature of the kiln was carried too high for the ingredients of the porcelain. It is rare indeed that visible "blebs" are found in electrical porcelain outside the factory. Perhaps this is because such pieces will be so soft at the high temperature that they will warp out of shape, and consquently they will be scrapped during the first visual inspection as they are taken from the kiln.

An unusual form of bleb has been found in one kind of porcelain, for which no definite explanation has yet been found. The bubbles are of varying size, all visible with the naked eye, and some of them are as large as one millimeter in diameter. These pockets or bubbles at the surface of a broken piece of porcelain were filled with eosin stain dissolved in alcohol and after thoroughly drying the stain the edge surface of the porcelain was ground off, thus decreasing the depth of bubble. It was found that the stain had soaked into the walls of the bubble to a depth greater than the diameter of the bubble. Here is an odd bleb surrounded by open pores. The porcelain was made in an experimental way and the bleb might have been due to a free flux as distinguished from a flux like feldspar in which the potash is bound up chemically until a high temperature is reached in the kiln.

Ceramists state that even the best porcelain contains minute cavities or pores of microscopic dimensions. This structure may be called the natural one for porcelain and the term " bleb " does not apply to it. It is probable that the granular or flaky structure of the porcelain is the characteristic that makes it less brittle than glass.

60. The Hot and Cold Test

Strains and laminations will usually be developed by a hot and cold test on the porcelain. This test has been used by a number of investigators and consists of transferring the porcelain periodically from boiling water to cold water. After a few transferences of this kind the insulator can then be soaked in stain under a vacuum to mark the cracked surfaces. A partial crack developed in this way will be completely developed by a high-potential high-frequency test. A complete crack from surface to surface of the porcelain will be indicated by a megger test. By using the megger test first it is possible to distinguish between partial cracks and complete cracks.

Regarding the question of the fairness of the hot and cold tests, we must again look to the conditions which occur in practise. It sometimes happens in certain climates that a hail storm will occur on a very hot day. The insulator and pin are at or above atmospheric temperature and a shower of hail or equivalent ice-cold water falls on the top of the insulator. This cools the upper exposed surface, leaving the lower ones warm. In the winter-time it occasionally happens that the temperature will change from a low value into a warm rain. This gives the insulator the other extreme of change of temperature.

It would seem from these two conditions that a hot and cold test carried over a range somewhat greater than that which may occur in practise is a justifiable test. It should be noted that the hot and cold test may develop mechanical strains in the porcelain which are present but normally are not faults. It is conceivable that a hot and cold test may produce strains and faults which did not exist before the temperature changes took place, due to a lack of elasticity in the porcelain and cement. Unless there is air in the porcelain it has not yet been determined whether such latent faults would always be developed with certainty by the electrical test, although the tests given would indicate that they would be. Theoretically the electrical test should strain the porcelain mechanically and might develop the faults. It should be recalled that we have shown by Fig. 23 that the electrical test when carried to the limit develops a puncture along those lines where shrinkage strains were greatest. Everything else being equal, we may tentatively infer from these tests that the shrinkage strains decreased the dielectric strength about 30 per cent.

61. Hot and Cold Tests Applied to Suspension Type Disks

Insulators from three different manufacturers, foreign and domestic, were used. The insulators were carefully tested to arc-over value and showed no puncture. The first set of hot and cold tests consisted in placing the insulators first in water at 66 deg. cent. and then in water at 9 deg. cent. for periods of 10 minutes each. Four insulators total were tested and none of them was cracked by this test.

In the next test the insulators were plunged into hot water at 100 deg. cent. for five minutes, then taken out and allowed to cool. In a subsequent test the voltage was not carried up to arc-over value but sufficiently high to give heavy corona discharge with potential from the oscillator. One of the four insulators punctured. We will designate these four insulators by A, B, C, and D.

Insulator D, the punctured one, was replaced by insulator D-1. The four insulators were again immersed in boiling water for 10 minutes, then plunged into cold water at 9 deg. cent. for 10 minutes. Insulator D-1 punctured under subsequent tests. Three more insulators were now added, which will be designated by B-1, C-1, and D-2. These insulators were then alternately immersed three times in boiling and three times in cold water at 9 deg. cent., each for 10 minutes. It was found that D-2 was punctured but all the others were normal. Insulators D-3 and D-4 were now added and all of them were again placed in boiling water for three minutes and in cold water immediately afterwards, and then tested. In this case no punctures were produced.

It should be noted that the insulators designated by C and D were made by one manufacturer and the difference in their ability to withstand the temperature changes was due to the form and vitrification of the porcelain and certainly not to the ingredients.

62. ADDITIONAL TESTS TO DETERMINE THE QUALITY OF PORCELAIN

Space does not permit of a description of other tests which have been made to determine the quality of porcelain, since it is desired here to show particularly the application of the oscillator and the new results which may be obtained with it. These other tests, however, are of varying importance and may possibly be given later. For example, the mechanical impact test with a varying weight is important in determining the fragility of the porcelain. Of the other tests along this line are the *ring of porcelain when struck*, *tensile strength*, *compressive strength*, *abrasive resistance*, tests for *toughness or brittleness*, *X-ray tests*, *microscopic investigation* with etching, *dielectric constant* as a basis of comparison, *absorption tests*, and so forth.

63. TESTS WITH CONTINUOUS HIGH FREQUENCY FROM AN ALEXANDERSON ALTERNATOR

It seems desirable to distinguish at this time between the results obtained by high-frequency wave trains such as are generated by the oscillator and continuous high frequency as generated by an alternator giving 100,000 to 200,000 cycles continuously. In practise there is no known strain on insulators corresponding to a continuous high frequency. Therefore there is no reason for using the high-frequency alternator in a standard test, much less, in fact, than for using 60 cycles as a standard test for insulators. However, the high-frequency alternator can be used in special tests to determine dielectric losses.

64. TESTING WITH WIRELESS OUTFITS

The usual apparatus used in sending wireless messages produces a series of wave trains of somewhat the same form as the oscillator already described. It is usual, however, to use a frequency of several hundred cycles per second in place of the 60 cycles per second. This gives a little more heating than an equal voltage furnished from the oscillator. There is a considerable difference in the practical handling of the two methods.

65. COMPARISON OF SMOOTH AND CORRUGATED SURFACED BUSHINGS

It is well known among designers that corrugation and petticoats on the surface of bushings increase the spark voltage. The following study was made to determine the laws of variation of spark voltage with increase of length of bushing, both smooth and corrugated.

Four test samples were used. No. 1, corresponding to curve 1, Fig. 31, was a porcelain bushing one inch thick, having a depth of corrugation of $\frac{1}{4}$ in. The thickness of porcelain in all of these data is always measured at the minimum point, that is to say, at the deepest part of the corrugation.

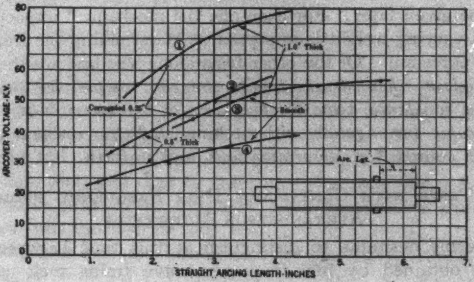


FIG. 31

The relation of length and thickness to the arc-over voltage in air of porcelain bushings and also a comparison of smooth and corrugated surfaces. Tests made with the oscillator. The relation is given between straight arcing length in inches and the kilovolts arc-over voltage.

Test piece No. 2, corresponding to curve No. 2, was $\frac{1}{2}$ in. thick with $\frac{1}{4}$-in. corrugations.

Test piece No. 3, corresponding to curve 3, had a thickness of one inch and a smooth surface.

Test piece No. 4, corresponding to curve 4, had a thickness of 1/2 in., and a smooth surface. These curves show the relation between the arc-over voltage and the arc length measured straight from electrode to the end of the test piece, but not taking into account the increased length due to corrugation and thickness at the end. The tests were made by placing a metal rod inside the porcelain bushing and placing a metal ring around the porcelain at different distances from the end to give different spark lengths in air along the surface of the porcelain.

To compare the corrugated with the smooth porcelain, curves 1 and 3 may be used, both having one in. thickness of porcelain, or curve 2 may be compared with curve 4, both pieces having 1/2 in. thickness. The effect of thickness can be obtained by comparing curve 1 and curve 2, both of which are corrugated, but of different thickness; or by comparing curve 3 and 4, both of which are smooth, but of different thickness. As an example, it is seen that for an arcing length of 3 1/2 in. and a thickness of one in., the arc-over voltage for a smooth surface bushing is 52 kv. Corrugating this surface with ridges 1/4 in. high raises the spark potential to 77 kv. From these data the relative effect of the corrugations can be seen. This relative value of corrugating is brought out by making comparisons of the spark-over voltages for different arc lengths at any desired point.

66. STUDY OF ARC-OVER VOLTAGE OF BUSHING, USING SUPER-SPARK POTENTIAL FROM THE OSCILLATOR

All the studies so far carried out have been on the basis of producing a design of porcelain of sufficient dielectric strength to withstand the voltages necessary to cause an arc-over when the applied voltage is gradually raised. This is the condition in the standard practise of testing as carried out today.

We are now to look forward to a more ideal design of insulators in which the requirements are going to be very much more severe. In practise, insulators are subjected to momentary lightning surges in which the potential may be very much above the value necessary to produce a spark. This high potential is very quickly relieved by the movement of the lightning surge along the circuit. If the relief is sufficiently rapid the super-spark potential may be applied to the insulator without causing an arc-over, simply because the arc has not had time to form. In line insulators it is absolutely essential that this super-spark potential shall not cause a puncture from electrode to electrode through the porcelain. The brief time required to puncture the porcelain must be greater than the time necessary to form the creepage spark around the skirts of the insulator through the air; otherwise a puncture will be produced.

In the case of porcelain bushings, the problem is somewhat different from the design of a line insulator. This difference comes from the fact that the porcelain bushing is used on a definite piece of electrical apparatus such as a transformer, motor, potential regulator, meter, etc., and there is need of a lightning arrester at this point. If it is possible and reasonable to do so, a porcelain bushing should also be designed with the criterion that it should always arc over before it punctures. We shall see later that this may lead to great difficulties and it may be deemed advisable by the designer to use a different basis. Since the bushing is protected by a lightning arrester in the neighborhood it should be possible to find a factor of safety against puncture of the porcelain which is sufficiently high to be above the maximum potential that can exist across the bushing as limited by the lightning arrester. At the present time this factor of safety is unknown, due principally to the lack of information regarding the voltages which may come from local oscillations, such as would create momentarily a higher voltage at the bushing than exists at the terminal of the lightning arrester. It is impossible to place all the lightning arresters quite near all the bushings which they are to protect. However, it is a tenable hypothesis that a factor of safety can be chosen which will put the spark potential of the porcelain bushing above the maximum potential that can exist across the lightning arrester for any intensity of discharge, with the exception of a direct stroke. If this standard of design is adopted a bushing may be used which cannot be tested to the voltage which would cause an arc-over. In other words, in a long bushing with much exposed surface to mitigate bad effects of dust collection, the requirements of test should be changed to suit these new conditions. The test should then carry the test voltage up to a value corresponding to the factor of safety chosen, say three or four. Nevertheless, the same standard made for the insulator is desirable for the bushing if it can be attained practically. To summarize, then, line insulators which have no lightning arrester protection must of necessity be designed so as to withstand a super-spark potential without puncturing, being always protected by an arc over the surface of the porcelain.

The plan is now to make an experimental investigation of what conditions must exist in porcelain bushings in order that the super-spark potential shall cause an arc-over rather than a puncture.

The first test is made on a smooth surface bushing ⅜ in. thick, with a length along the surface of 1.9 in. The generated potential of the oscillator was gradually raised in successive steps from the arc-over voltage (27 kv.) to its maximum value of 170 kv. corresponding to 10 kv. on the control gap shown as abscissas in Fig. 32. As the momentary impressed potential is increased from 27 kv. to double that amount the gap in parallel with the bushing shows an increase in potential from 27 kv. to 32 kv. This increase of 19 per cent in the equivalent spark voltage at the terminal of the bushing for 100 per cent increase in the applied super-spark voltage represents a logarithmic time curve of discharge, the time decreasing rapidly with the increase in voltage. When the super-spark potential has been increased to 24 times the arc-over potential, the equivalent gap in parallel with the bushing shows a maximum rise of voltage to 50 kv., which is slightly less than twice the arc-over voltage.

From the point of 24 times the arc-over voltage, to the super-spark potential of 40 times the arc-over voltage, the equivalent gap in parallel with the bushing increases only 2 kv. more. In other words, the maximum possible potential that may be impressed on this bushing is of the order of double the arc-over potential. We might look forward at this time to our method of design. If we were choosing the thickness of this bushing for a design that would withstand super-spark potential without puncture, we would turn to a puncture curve of porcelain under oil and choose from this curve a thickness and grade of porcelain which would not puncture on 50 kv. applied. This bushing would then arc over for super-spark potentials of 175 kv. at 300,000 cycles and should be proof against puncture.

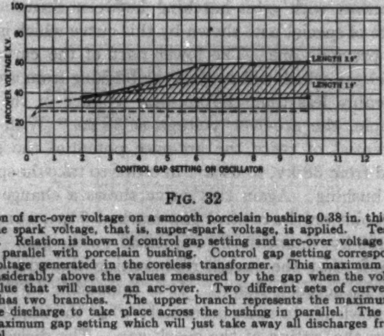


FIG. 32

The relation of arc-over voltage on a smooth porcelain bushing 0.38 in. thick when voltage above the spark voltage, that is, super-spark voltage, is applied. Tests made with the oscillator. Relation is shown of control gap setting and arc-over voltage as measured by a gap in parallel with porcelain bushing. Control gap setting corresponding to the maximum voltage generated in the coreless transformer. This maximum voltage generated is considerably above the values measured by the gap when the voltage is above minimum value that will cause an arc-over. Two different sets of curves are shown. Each curve has two branches. The upper branch represents the maximum gap which causes all the discharge to take place across the bushing in parallel. The lower branch shows the maximum gap setting which will just take away all discharges from the bushing in parallel.

In this same set of tests another factor was studied, namely, the factor usually determined in the design of lightning arresters. What gap must be placed in parallel with the bushing such that the discharge will always take place over the parallel gap rather than over the bushing? In terms of lightning arrester design, what equivalent gap must a lightning arrester have so that it will always take the discharge of high potentials away from a bushing and thereby give it protection from arc-over? In Fig. 32 the lower branch of the curve shows a practically constant voltage setting of 28 kv. on the gap to take the discharge, even when the super-spark potential was as great as 175 kv.

In the next step the length of the same smooth surface bushing was increased from 1.9 in. to 3.9 in. The same system of tests was applied and is shown (Fig. 32) in the corresponding pair of curves with cross-hatching between them. There is one feature of special note shown by this curve which is different from the previous one. The lower part of the curve, that is, the parallel gap which will protect the bushing from arcing over, is considerably less than the arc-over voltage of the bushing. For example, the arc-over voltage is 38 kv. With a super-spark potential of twice the arc-over potential the gap must be reduced from 38 kv. to 34 kv. in order to take the spark away from the bushing. Again this curve shows a change of direction at a point on the control gap marked 6 kv., corresponding to about 100 kv. momentarily impressed on the gap. We must not conclude that the curves representing the equivalent gap in voltage are actual voltages. It is impossible in the present state of knowledge to state accurately what the impressed voltage is from the setting of the spark gap. The dielectric spark lag enters therein, and is affected by various conditions. We must take into account also that the impressed frequency in this case is about 300,000 cycles and that the equivalent gap would change somewhat by a change in the frequency, this being due to a relation between the wave front and the dielectric spark lag of the gap.

67. Further Tests with Super-Spark Potential

In Fig. 33 are shown two sets of curves taken on bushings with corrugated surface. The sparking length of bushing in the lower curve was 1.75 in. and in the upper curve 3.9 in.

As before, the abscissas are proportional to the applied super-spark potential and the ordinates represent the potential as measured by the sphere gap. There are two curves for each setting of the super-spark potential, one minimum equivalent gap which takes all the discharge and one maximum equivalent gap in which all the discharge is transferred to the bushing which is connected in parallel with the gap.

These curves show the same general outlines as the previous tests on smooth-surface bushings. The corrugated bushings, however, show a very much higher test of voltage, which is due to the greater difficulty in forming a creepage spark over the hills and valleys of the corrugations. The spark will run over the outside surface, parallel to the conductor in the center of the bushing, fairly easily, but when it has to climb one of the ridges of the corrugation at a considerable angle to the central conductor it requires a very much higher voltage to produce the creepage spark. Once over the ridge the spark can again dart down into the valley of the corrugation with ease but is again retarded as it climbs the next ridge of the corrugation. This condition has been illustrated elsewhere and it does not seem necessary to reproduce the illustrations at the present time.

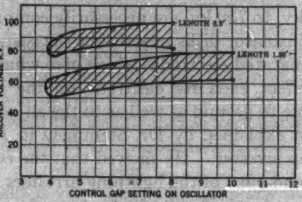


Fig. 33

These relations are entirely similar in every respect to the curves given in Fig. 32 except that the thickness of the bushing was one in. and the surface was corrugated with ridges 0.25 in. high. (In the lower branch of the upper curve, at 6 kv. setting on the control gap, is an error. It should be 82 kv.)

FORMULAS FOR THE LAWS OF VARIATION OF SUPER-SPARK POTENTIAL VERSUS ARCING LENGTH ON CORRUGATED BUSHINGS

Many tests were made on different forms of insulators and it was found that the law of creepage spark was usually of the nature of an exponential curve within the range of lengths and thicknesses studied. The different formulas need checking in extrapolated points and for this reason they are not published at the present time. The points given for the curves of super-spark potential fall approximately on a straight line when plotted on logarithmic paper. The curves are represented by the following formula:

$V = 50\, t^{0 \cdot 682} L^{1 \cdot 06}$ (porcelain corrugated)
V = Maximum measured super-spark voltage in kv.
t = Minimum thickness in inches
L = Distance from outer terminal to end of bushing in inches.

68. Testing of Strings of Insulators with the 300-kv. Oscillator

When the problem of testing disk insulators in strings is undertaken the oscillator shows some marked advantages over the 60-cycle method. The oscillator has dimensions and cost which are only a small fraction of a 60-cycle outfit. In designing 60-cycle transformers there is nothing gained by using extremely small wire and therefore the dimensions of the transfomer for a voltage of 500 kv. to 750 kv. are necessarily comparatively large.

The several insulator disks in series in the suspension type insulator have separated electrodes which give what may be called the multi-gap effect, each iron electrode on the insulators having a capacitance to ground as well as to the adjacent one. This theory was first explained by Dr. Steinmetz in 1906 in relation to the multi-gap arrester. He showed that the concentration of voltage at the end gaps of the lightning arresters was due to the capacitance of each metal cylinder to ground. It is now common knowledge that the same condition exists in a string of suspension insulators and the voltage is unevenly distributed throughout the string, as has been shown by several investigators. The disk next to the line takes the largest percentage of voltage.

After noting this theory, it is somewhat confusing to find that in testing a string of insulators it is not the end disks which are most liable to puncture. Some tests were made which show that the insulator farthest from the end is the one most frequently punctured by the high-frequency wave trains from the oscillator. Five insulators were placed in series and connected to the oscillators, having no ground at either end. This places the third insulator at zero or earth potential. Out of 21 insulators punctured, 13 of these were in the location of the third disk, four were in the location of the second disk, and two in the corresponding symmetrical location of the fourth disk. There was only one insulator at each end of the string that was punctured in all the tests. Making comparisons between these different conditions, the middle disk of a string of five punctured 13 times as many times as the end insulators. It also punctured 3 to 6 times as many times as the adjacent disks on each side of it.

The explanation of this phenomenon seems to be that of difference in super-spark potential on the disks in the different locations. As a tentative explanation the following is given: When the high-voltage high frequency is applied to this string of insulators the distribution of potential gives the greatest potential at the end disk and the least at the middle disk. However, the total voltage applied to the end disks is not extremely high, because of the partial distribution along the string. The applied voltage is somewhat higher than the value necessary to cause a spark. The end disk sparks over and there is thrown suddenly on the three remaining disks a super-spark potential of considerable value due to the short-circuiting of the end disk by the spark. The duration of time considered is of the order probably of a few millionths of a second. The total voltage applied in these tests, approximately 350 kv., is now divided somewhat unequally between the three disks. If the second and fourth disks are not punctured by this excess voltage they will spark over and the middle disk for a moment will receive a voltage of nearly the full value of 350 kv. As a result the middle disk is very liable to be injured.

The effect obtained by the concentration of voltage on the end disks and their successive elimination by sparking around the skirts of the disks is very much like using one insulator on this oscillator and suddenly discharging against it an impulse of 350 kv. The actual spark potential of the disk is about 85 kv., which leaves a super-spark potential of 265 kv. This effect is exactly like the one obtained from a lightning stroke on the line. I think it very probable that operators of transmission lines can confirm the statement that lightning does damage disks from time to time that are nearer the ground terminal than the line terminal of the string of disks.

It is important to add further information in regard to the duration of the tests. In each case the 60-cycle potential was applied to the oscillator for a period of five seconds. The test was then discontinued for five seconds, giving the insulators a rest, and then re-applied. In order to puncture the middle insulator the number of applications of five seconds duration is given as follows: 8, 7, 21, 9, 1, 18, 4, 50, 18, 16, 10, 8, 1.

The number of applications of five seconds each to puncture the six adjacent disks, namely the second and fourth in the string, was as follows: 30, 1, 39, 16, 8, 3. For the end disks, namely the first and the fifth, there were 9 and 11 applications of five seconds duration. Each second represents 120 wave trains applied to the insulator, so that each application, as given in the above list, means 600 wave trains discharged against the string.

In the data given above there is no statement made of the number of times that the impulses were applied without causing damage. The method of test was to continue to apply the voltage to the string of insulators for five-second periods until at least 50 applications could be made without damage to the string of insulators. Then a new string was installed, and as fast as the disks were punctured they were replaced until the string showed its ability to withstand the tests. In the first string there were 50 applications of five seconds duration finally applied without causing damage. In the second string 120 applications were finally made without causing punctures. In the third string there were also 120 applications without causing puncture. In the fourth string of insulators there were 50 applications without causing puncture. These tests tend to show that the insulators are designed so that they can withstand this test. It is an extremely severe test and under present conditions of knowledge and manufacture it would seem to be unfair by being unduly severe. The tests are given not as recommendations but as information on the subject.

In regard to the location of the punctures, 50 per cent took place in the head of the disk and 50 per cent at an average distance of one in. out on the porcelain skirt. Another series of tests was made in which the duration was only ½ second, with two-second intervals of rest. It was found that a shorter duration was of very much less severity to the porcelain than the longer duration. Damage is therefore being done to the porcelain in a manner which will be illustrated later, under potential gradient tests. While the arc-over potential of these disks was in the neighborhood of 85 kv., the puncture potential under oil was 128 kv. and 150 kv., which gives a factor of 150 per cent and 176 per cent. The study of the necessary dielectric strength to puncture, similar to the one already given for bushings, could be made with an oscillator and thereby determine what factor is necessary in order that the suspension disks shall always spark around the skirts rather than puncture. No previous tests were made under oil on any of the disks that punctured to determine if their factor of safety was as high as the two given above. It is desired at the moment simply to point out that it is a comparatively easy investigation to make with the oscillator, although precaution must be taken to limit the duration of the test to the value that will not cause local damage to the porcelain by corona in accordance with the values determined from the potential gradient tests, examples of which are given later.

69. POTENTIAL GRADIENT TESTS WITH THE OSCILLATOR NOT CARRIED TO PUNCTURE OF THE PORCELAIN PIECE

Test piece was a porcelain bushing, 13 14/16 in. long with a minimum diameter of 3 10/16 in. outside and 1 6/16 in. inside, approximately. The thickness of the porcelain was 0.94 in. From bottom to top, as it stood in drying and in firing, there are eleven grooves on the lower half and nine grooves on the upper half. The tests were started on the top groove, No. 20. Inside the porcelain tube an iron pipe was placed and on the outside was placed our standard electrode, which is 0.12 in. thick and 2 in. wide, rounded at the edges. The porcelain was immersed under transil oil to a depth of 2 in. The duration of application of voltage in every test was five seconds. On the 20th or top groove the first potential applied was 60 kv., and in each succeeding groove there were 10 kv. added. When 120 kv. was reached and applied for five seconds the porcelain punctured. The detailed results of these tests follows.

TESTS WITH VARIABLE VOLTAGE BUT 5 SECONDS CONSTANT DURATION

Groove. No.	Kv. applied.	Comments
20	60	No visible damage to the surface.
19	70	“ “ “ “ “ “
18	80	“ “ “ “ “ “
17	90	A very definite black streak was produced on the ridge.
16	100	Only a very slight marking on the surface.
15	110	More evident damage to the surface.
14	120	The porcelain was punctured and a piece ½ in. wide was chipped off.
12	60	No visible damage done to the surface.
11	70	“ “ “ “ “ “ “
10	80	Small piece of glaze chipped out on the side of the ridge and a black deposit at the bottom. Length two mm.
9	90	Very visible damage done, chipping out the glaze for about 2 millimeters and producing five definite black spots. There was one puncture hole through a bubble in the glaze and the puncture ran in various directions to the other five spots, all of which are bubbles in the glaze.
8	100	Although the voltage was higher there are only two very small spots where the corona broke through the glaze.
7	110	Again a very appreciable piece four mm. long chipped out of the glaze.
6	120	Punctured, leaving a small black spot, showing a superficial crack about 25 mm. long running across to the next groove.
4	80	No visible damage done to the surface.
3	90	Punctured. A chip about three mm. wide and five mm. long was thrown out of the surface. A crack 10 mm. long was caused by this puncture.
1	100	No visible damage done to the surface.

Further Comments. A microscopic examination was made from 25 diameters to 250 diameters. The damage to the surfaces is done by the combination of potential gradient and heat of the corona. It seems evident from these tests that there is a considerable difference in the dielectric strength of the porcelain in different spots, as evidenced by the fact that some, say at 100 kv., did not scar the surface where tests at 90 kv. did. This naturally leads us to the possibility of examining the homogeneity of porcelain by means of potential gradient as distinguished from the ordinary potential tests. Such a study will be described later.

70. POTENTIAL GRADIENT TESTS ON PORCELAIN WITH THE ELECTRODES SO ARRANGED THAT PUNCTURE COULD NOT TAKE PLACE

In the previous test given, the lines of electrostatic force were perpendicular to the surface of the porcelain, due to the fact that a long metal electrode was used inside the porcelain bushing and the other electrode was placed against the surface in a valley of a corrugation.

In the test now to be described the internal electrode was removed from the bushing and placed in the oil at a horizotal distance of 9 in. from the center of the porcelain bushing and at about the same distance from the other electrode which rested on the upper surface of the bushing. The lines of electrostatic stress were carried through the porcelain to a certain greater extent than through the oil, due to the fact that the dielectric constant of porcelain is about 2½ times that of oil. However, there was no tendency to puncture the main body of the porcelain and the only effect obtained was the intense voltage gradient at the surface of the porcelain on which the small electrode rested.

In the first group of tests the time of application was 10 seconds and the potentials used varied in the seven different grooves tested from 120 kv. down to 70 kv. The general results of these tests were negative, that is to say, no markings were caused by the potentials applied.

In the second group of tests the porcelain bushing was rotated about 80 deg. from its previous position. The time of application of potential in each of the ten tests made was five seconds. The results show the gradual development of faults.

Groove No.	Kv. Applied.	Comments
1	70	No visible damage to the surface.
2	80	No visible damage done to the surface.
3	90	A visible black speck on the glaze of the bottom of the groove.
4	100	" " " " " " " " " " " "
5	110	Slightly larger speck.
6	120	Same size of speck as previous test.
7	130	Same size of speck as previous test.
8	140	Visibly larger speck.
9	150	A black streak about two mm. long. During the test a visible glow was seen through rather dark oil at a depth of 3 in. at the contact of the electrode and the surface of the electrode.

Comparing the second group of tests with the first group, it should be noted that in spite of a reduction of time from ten seconds to five seconds, damage was done at the same voltage, which indicates, perhaps, weaker porcelain.

In the next test, which was made on groove 10, the time of application of potential was increased from five seconds to 30 seconds and the voltage was maintained at 150 kv. As a result a black streak about three mm. long was produced on the surface of the porcelain. A microscopic examination showed two puncture holes in the glaze and a black streak running along the surface of the porcelain. The diameter of the punctured holes in the glaze was about equal to the size of the bubbles in the glaze.

In the third group of tests the time was made uniformly 30 seconds for each step. The same angular position was used as in the previous tests but the distance was 3½ in. farther up on the bushing.

Groove No.	Kv. Applied.	Comments
12	100	No visible damage to the surface.
13	120	A glow at the electrode visible through the oil. A streak about 5 mm. long was produced on the side of the ridge. Some glaze was chipped off.
14	140	Same glow as before. Small black speck produced on the side of the ridge.
15	160	Visible glow through the oil. A circular piece about 2 mm. in diameter chipped out of the glaze on the side of the ridge and a streak 10 mm. long extending at an angle down the ridge.

Conclusions. So far as the data go we must conclude that the quality of the porcelain varies at different points of the surface. The damage is apparently done by an extra large displacement current at the surface which causes local heating by the spark. These tests apparently indicate a new method of investigation of homogeneity of porcelain. They have not been carried far enough to determine all the causes of differences found.

71. AN EXAMINATION OF THE SURFACE OF A PORCELAIN BUSHING BY VOLTAGE GRADIENT TESTS

After considerable preliminary work the following basis of test was determined upon. A corrugated porcelain bushing of uniform thickness was immersed in oil with a rod 3/16 in. diameter through the center of it. Around the bushing in the valley of a corrugation was placed a copper wire 0.05 in. diameter. Between these two electrodes there was applied 120 kv. during a period of five seconds, using the oscillator as a source of power. As a result, the voltage gradient at the surface of the wire caused more or less small black spots or scores. The electrode was then moved into the valley of the adjacent corrugation and the test was repeated until all the 20 corrugations were covered. An examination was then made of the surface of the porcelain and it was found that in certain localities there were no spots and in certain other localities there was a considerable number of spots. The development of the surface of the porcelain is shown in Fig. 34 with the location and the relative sizes of the spots.

Since at the start the potential gradient at all parts of the encircling wire was quite uniform, these tests show a difference in the dielectric current in the porcelain. The exact nature of this difference is not determined at the time of writing but it is evident that it represents a difference in homogeneity of the porcelain. It cannot be stated that this difference represents a serious or important difference in this particular piece of porcelain. At the same time it would seem that this electrical method would be a convenient one for examining variations in the porcelain as they might be affected by non-homogeneous distribution of ingredients, by drying, or perhaps some other factor.

Knowing that the bubbles in the glaze are the beginning points of the damage to the surface and still further knowing that the expansion of a spark into a bubble would give a greater concentration of voltage gradient at this point, it was thought possible that the beginning of the trouble was due entirely to the accidentall ocation of bubbles in the glaze. While this may be true, it was necessary to make further tests to determine if there was a real difference in the quality of the porcelain underneath the glaze. The porcelain bushing was taken to a carborundum wheel and the glaze was carefully ground off in the valleys of the corrugations. The previous tests were then repeated and are shown in the three lower lines of Fig. 34. The damage done in the previous tests was entirely superficial and the black spots disappeared during the grinding off of the glaze. The new spots shown for corrugations 13, 7 and 3 occurred in the same general locality that they did in the previous test when the glaze was present. This tends to prove that the porcelain varies in quality throughout the bushing.

72. When Does the Test Damage Good Porcelain?

It was found in the voltage gradient tests that when the voltages over 100 kv. were applied the damage to the porcelain started in a definite spot and within a few seconds the damage was gradually increased until puncture finally took place. By making a few preliminary trials it was possible to determine roughly the law which determines the voltage and time of application which would damage the surface. These time-voltage applications were then made over the different parts of a porcelain bushing and as a result a certain number of spots was obtained for each application. The spots varied in diameter and somewhat in number. Therefore a certain arbitrary weight was given to the

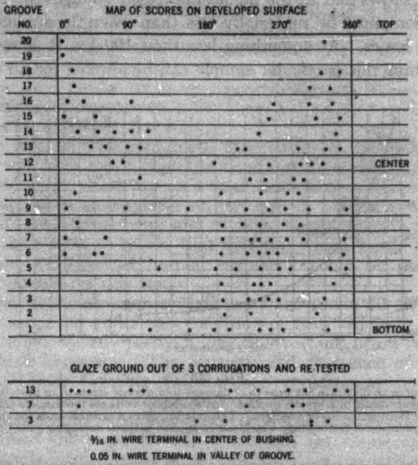


Fig. 34

Map of scored surface of a porcelain bushing to which was applied a voltage gradient test. 120 kv. was applied ten seconds. The small black spots represent the beginning of puncture. The variations in the location of the spots over the surface of the porcelain are presumably due to variation in the quality of the porcelain. The small map below shows three tests on grooves which had the glaze ground off. The electrode was a wire of 0.05 in. diameter wrapped around the valley of the corrugation in each of the above tests.

size of the spot and the number of spots was taken as a criterion of damage done. Small spots were given a weight of 0.8 of the average. Large spots were given a weight of 1.2 of the average size of spot. Then the time voltage tests which gave approximately the same number of spots were chosen. The results are plotted in Fig. 35.

It must be confessed that this is a rough method of arriving at the curve and yet it is of fair reliability for this quality of porcelain. It shows that at the higher impressed voltages the time of application must be materially less than when the applied voltages are lower. At something less than 100 kv. it shows that the tests on this particular sample can be applied for an indefinitely long time without starting a fault by concentration of voltage at the electrode.

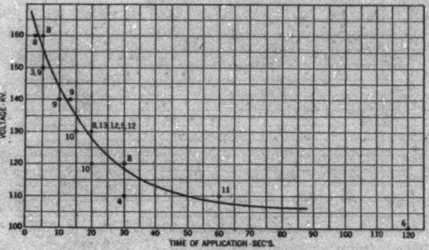


Fig. 35

A rough curve to illustrate the growth of damage to dielectric strength in porcelain bushings at different values of kilovolts applied. At the higher voltages the damage takes place more rapidly than at the lower voltages. This relation gives a rational basis for the proper period of application of test voltage which can be applied without damaging good porcelain.

This is the first step in laying out a rational rule for testing of porcelain. Other tests are being made, using wires of larger diameter with corresponding variations in the values of potential gradient in order to determine the law of potential gradient versus damage to the porcelain. The potential gradient is extremely high as compared to the value that causes corona in air (30 kv. per cm.).

In developing the oscillator and gathering the data herein presented the author takes pleasure in acknowledging the assistance of Messrs. P. E. Hosegood, S. Thomson and G. F. Gray in the development of the oscillator and of Messrs. R. H. Forney and R. H. Marvin in the experimental studies.

DISCUSSION ON "ELECTRICAL PORCELAIN," (CREIGHTON), NEW YORK, FEBRUARY 19, 1915.

A. O. Austin: The oldest impact method used in testing insulators is probably that of suddenly throwing in the switch on the primary of the testing transformer. This is rather uncertain, but usually results in a rather severe surge or suddenly impressed voltage on the insulator, and will puncture material which can not be weeded out where the voltage is held on continuously, even at the point of flash-over.

Where the voltage rises very suddenly, there is not time for the shunting corona or streamers on the insulator to build up, consequently, insulators of very poor design are likely to have very severe stress thrown upon them before they will arc to flash over, and limit the voltage.

This method was used quite extensively in 1904 and 1905, but it was later found that the same results could be obtained by running the alternator on a weak field, so that the arc would snuff out when an insulator or part spilled. When a part arced over, surges were set up, and it was comparatively easy to make these tests so severe that material which would show no apparent weakness at normal frequency could be practically all eliminated on this test.

It was not uncommon several years ago to see 50 per cent of the material fail under this condition of test, although the material had previously passed a long time test just below flash-over at normal frequency. The capacity and reactance of the test pans and leads, together with the poor regulation in the alternator, are all that is necessary to make this a very effective test. The flash-over of the insulators produces considerable noise, and unless the room is well ventilated, the ozone and other compounds formed make it very difficult for one to breathe.

This method of testing has been in constant use since the latter part of 1905, and I believe is one of the best high-frequency or impact methods for commercial work.

A slight variation of this method was put into use in 1909. This method consisted of placing a gap in series with the several parts, and was developed to test assembled suspension insulators. The gap was placed in series in order to detect an insulator which failed inside the cap, but it was soon found that if the gap was eliminated or was too small, the severity of the test was very much reduced, particularly where one insulator was tested at a time.

The series gap cuts out part of the wave, giving the corona or streamers less time to build up, which permits of a higher stress being thrown on the insulator. There is, also, an oscillation set up by the sudden spilling. This method is somewhat similar to that described in a paper by Thomas and Imlay, but, of course, is very much milder, being applied to routine work.

Where this method was used, pieces were tested in lots of from one to seventy. It was found to be better practise, however, to test only one piece at a time, as pieces have to be observed very carefully on this test, for the high-frequency discharge will not usually continue through the same path, the damaged pieces easily escaping notice unless the particular piece is under careful observation at the time. Fig. 1 shows insulators which have been punctured in the flange by this method, and Fig. 2 shows a large number of insulators under test at one time, using this method.

There is a great similarity between these failures (Fig. 2) and those obtained in service, some examples of which are shown in Fig. 3.

There is no doubt as to the effectiveness of these tests, and they have the advantage that they are quite reliable under ordinary conditions. They have the disadvantage, however, that the frequency may vary greatly, and unless the apparatus is well protected, there is danger of a breakdown.

The oscillatory transformer will give considerable data as regards the frequency of many faults developed in service, but where the apparatus is used for commercial testing, it is important that it be well designed, otherwise, the results may be uncertain. The work of Professor Creighton along this line should make this piece of apparatus particularly valuable for commercial testing, either at the factory or in the field.

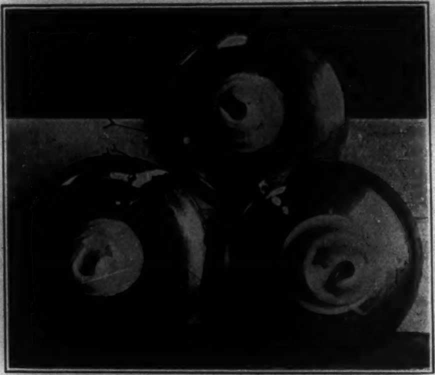
To make a piece of apparatus of this kind effective for commercial testing requires much careful work, and Professor Creighton certainly deserves much credit for perfecting the oscillatory transformer, for testing purposes. The light weight of this piece of apparatus, and its low cost compared to the usual high-voltage testing sets, make it available for a large class of work.

In discussing high-frequency methods, it is well to keep in mind some of the theoretical considerations adopted in insulator practise.

In Fig. 4 are shown two insulator parts tested in multiple at normal frequency. The larger part, having a surface distance of 19½ in. and a striking distance of 14 in., has a flash-over of 75 kv. at 60 cycles; the smaller shell or part, having a surface distance of 9½ in. and a striking distance of only 6½ in., has a flash-over of 80 kv. under the same conditions.

It will be seen that at normal frequency it is possible to test the small insulator to a higher voltage than the larger one, and if tested in multiple, and at normal frequency, the larger part will always flash over first.

If the two parts are connected in multiple, and a gap in series, it will be found that the small insulator will often flash over first. This will indicate that the small protecting air path of 6½ in. will break down before the 14-in. air path on the larger insulator, and hence the danger of the smaller insulator failing in service is much less.



[AUSTIN]

FIG. 1

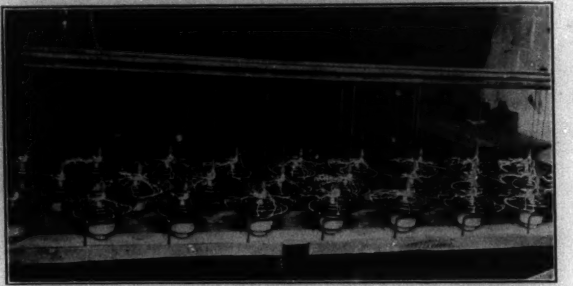


FIG. 2

[AUSTIN]

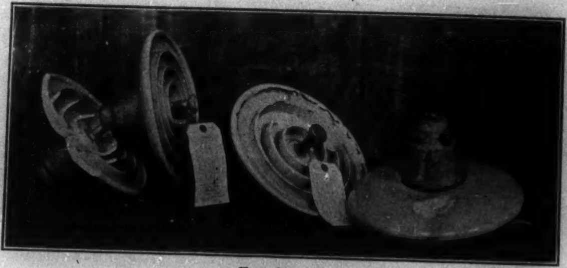


FIG. 3

[AUSTIN]

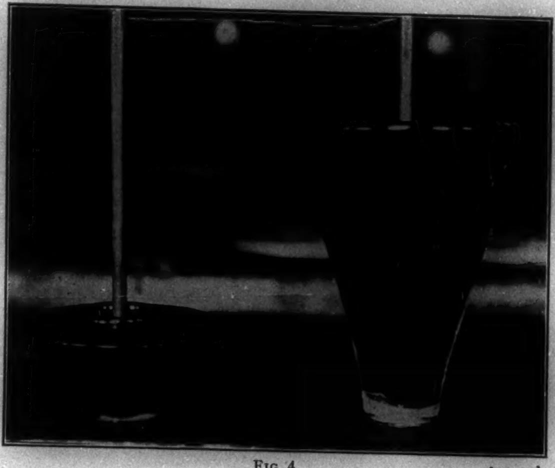


FIG. 4

[AUSTIN]

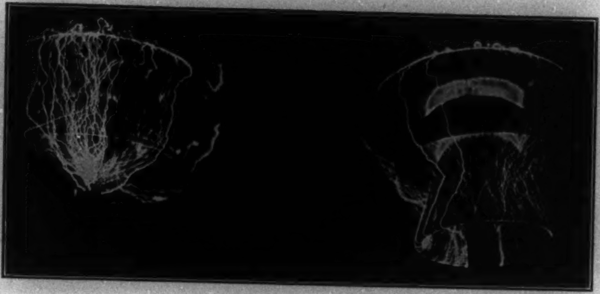


FIG. 5

[AUSTIN]

FIG. 6

[AUSTIN]

If, in place of using a surge having a very steep wave front, the frequency is increased gradually, starting at 60 cycles, it will be found that the flash-over of the larger insulator will be lowered much more rapidly than the smaller one as the frequency increases.

This is not surprising if we consider the nature of the performance, for the low flash-over of the larger insulator is due to the static streamers building up over the surface, which shunt much of the surface, as these streamers are in the nature of a conductor of high resistance. As the frequency increases, the current in these streamers is increased and the shunting action greatly increased, thereby lowering the flash-over.

If the frequency reaches an exceedingly high value, it is possible that the small streamers will not have time to build up before there is a reversal of stress, and a point will be reached where an increase in frequency will tend to increase the flash-over value of the part.

In practise we usually have surges of the highest frequency in the case of lightning, and those of a comparatively low frequency due to arcing grounds, with very few disturbances of the intermediate frequency.

If impact tests are applied to an insulator having the characteristic of the larger insulator shown in Fig. 4, good material may be destroyed. In case of the smaller insulator, however, it would be much more difficult to destroy good material, for not only does the smaller insulator have lower maximum stresses but the short protecting air path operates to save the insulator.

In service an arcing ground, while producing a surge of much higher magnitude than the operating voltage, tends to lower the flash-over voltage compared to that at normal frequency on insulators having the characteristics of the larger one shown in Fig. 4.

On the other hand, their effect is very slight in lowering the flash-over voltage in the case of the smaller insulator. A test frequency of several thousand cycles, while making little difference in the case of the smaller insulator, would so lower the flash-over of the larger insulator that the test would be very mild.

In the case of lightning, either insulator would probably not be large enough to prevent spilling, but whereas the larger one with the 14-in. protecting air path might fail, the small one would probably pass undamaged.

If insulators made up of parts similar to the smaller one shown in Fig. 4 are used, much trouble experienced on transmission lines is eliminated, even where they replace insulators having a higher flash-over at normal frequency.

If we make tests on insulators of this type under sudden impact, we are likely to assume that much trouble will be encountered in practise, as these insulators will spill much more more readily than insulators having the characteristics of the larger one shown in Fig. 4.

If we will consider, however, that lightning or switching is practically the only disturbance that produces a severe impact in service, and that increasing the striking distance of the insulator 50 or 100 per cent will hardly prevent spill-overs, it will be seen that we have little to fear from this source. If in addition to this, we take into consideration that the smaller type of insulator will not spill as readily as the larger one under the frequency produced by an arcing ground, it is readily seen that no trouble need be experienced from the small insulator spilling, owing to its short striking distance and small dielectric spark lag.

Much time and expense has been spent in the last three or four years in obtaining a short air path, so as to cut down the dielectric spark lag for the protection of the insulator, and an examination of insulators on a good many lines shows that there is probably ample strength in the better types of insulators.

In Fig. 5 are shown two pin type insulators being tested in multiple. These insulators are under the normal stress of 60 cycles, as well as high-frequency disturbances. The insulator shown on the right has a striking distance about 20 per cent greater than the insulator on the left, and at normal frequency has a lower flash-over value.

Under impact, or a wave with very steep front, the insulator on the left will flash first. The very fine streamers are produced by the high frequency and the large bright streamers are probably high-frequency discharges which have been combined with the normal frequency, or constitute the heavy rush of current when the capacity of the apparatus first discharges.

In operation, the insulator on the right would flash over much more readily with an arcing ground on the system than the one on the left, but owing to its greater striking distance, and dielectric spark lag, a much higher voltage would be piled up before it would spill if struck by lightning.

Even if the insulator had the same dielectric strength as the one on the left, the increase in stress of 10 or 20 per cent would increase the probability of failure a great many times. It will be noted in this illustration that the streamers have a strong tendency to follow the surface, particularly in the case of the insulator shown on the right.

In Fig. 6 is shown a suspension disk tested under conditions described in the second method. It will be noticed that many of the streamers follow every irregularity in the surface, similar to those obtained with the oscillating transformer.

If the oscillating transformer can be used to produce conditions of this kind with the wide variation and capacity produced by the varying types and quantities of insulators, it will indeed prove a valuable means of testing, for there is no doubt as to the effectiveness of the conditions under which this insulator is tested.

In 1909 a lot of over 15,000 insulators was tested in this manner for one minute and later tested to between 50 and 60 kv. for fifteen minutes. In all this quantity only one insulator was recorded as broken down on the 15-minute test, and there was some doubt as to whether this insulator had not been removed on the previous test.

On the basis of this record, the long-time test was abolished in favor of a short-time test at a higher voltage, for the high-voltage test removed approximately 5 per cent of the material, and the 60-kv. test less than one fourth of one per cent when applied first.

It is not advisable to use tests of too high a magnitude on a single part, for this will result in designs which work the material under test conditions so mild that many pieces having serious defects may find their way onto a system to cause trouble at a later time. No severe design test, however satisfactorily made, on a few insulators only, can insure good operation on a large system if there is even a comparatively small percentage of faulty insulators which are let through on the routine tests.

There is much information to show that it is not necessary to design the parts or even the complete insulators so that they will withstand the severest laboratory tests.

On the other hand, some insulators which show very fine results on impact or high-frequency tests have had to be replaced for the time-puncture rate, for the quantity was too high, causing many interruptions on a large system.

In any but the poorest insulators, the mechanical stresses are far more to be feared than the electrical. It would appear that no one test is sufficient, and that factory routine tests will include tests at normal frequency, high-frequency or kick tests and resistance tests.

Each test has advantages in eliminating certain classes of material; and it is possible to insure maximum reliability without carrying a test to the point where good material is destroyed or damaged.

High-frequency or impact tests tend to eliminate many faulty designs, but too much dependence must not be placed in the test method, for an insulator may fail for many different reasons other than lack of strength to withstand the impact test.

Crosby Field-Frank: When a new system of operation or a new process is invented or first introduced, we are sometimes quite skeptical not only as to whether it is absolutely correct in theory, but also how it will act when put into the factory. I had the pleasure of using one of the first oscillatory transformers in a factory for testing bushings, and must emphasize the ease with which the machine operated and the definiteness of the test. There never was any doubt when the insulator was punctured. The test was absolutely certain.

I would also like to emphasize Mr. Creighton's remarks about the effect of the high-frequency test upon those bushings which had previously passed the 60-cycle test. If I remember correctly, the percentage of rejections on the high-frequency test of those which had previously passed the 60-cycle test amounted in some cases to as high as 17 per cent, and in other cases to zero per cent, an average somewhat in the neighborhood of 7 per cent.

J. T. Lawson: In operating our 13,000-volt transmission system we experienced trouble from insulator and cable failures, and for the last three years we have given considerable thought and study to correct them. Relative to this, I call your attention to the discussion at Detroit by Mr. Osgood, printed in the February number of the Institute's PROCEEDINGS.* This discussion covers the work we have been doing. Adding a little more detail to this discussion, I wish to point out that with an increase of 160 miles of transmission, we have succeeded in two years in cutting the number of our service interruptions, due to the failures of insulators and underground cables, from sixty-five in 1913, to forty-five in 1914.

As brought out by Mr. Osgood, we found that our chief cause of failure was the insulator, which, when failures occurred, set up disturbances which in turn caused a breakdown on the cable in our underground system; therefore, to correct our service troubles, the place to start was on our line insulators.

The first year of work was taken up by testing with high potentials at 60 cycles, but beyond the fact that the tests proved we had bad insulators on the lines, which was already shown by service conditions, we were unable to arrive at any means to correct our insulator faults by this method.

Changing our methods, we started testing with the oscillating transformer, using samples of insulators taken from our lines. In this manner we were able to see at close range, without anything to divert our attention, in what respects our insulators were weak. In this feature the oscillatory transformer has the advantage over all other means of testing. The voltage is under complete control, and once set, the insulator can be subjected to a certain potential for as long a time as desired with an ease that cannot be done with any other method. At the same time, the entire surface of the insulator is completely covered and all weak spots can be found.

The methods adopted in conducting these tests were as follows: Pin type insulators were racked and tested singly, the disk type was suspended and tested in pairs. The first 250 insulators tested were subjected to spark-over voltage for a period of one minute, the voltage being built up gradually from zero to spark-over voltage. As all failures of this group occurred within five seconds after obtaining maximum voltage, the period was shortened to thirty seconds. As the failures in test also occurred within the first five seconds, all succeeding insulators were tested for only fifteen seconds, the set running continually at spark-over voltage, the contacts being changed from insulator to insulator.

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*TRANS. A. I. E. E., 1914, Vol. XXXIII, Part II, p. 1128. PROCEEDINGS A. I. E. E., Feb. 1915, p. 308.

The benefits to be derived from this testing are brought out in the results obtained from a new forty-mile transmission line recently erected. This line was in service using an older type insulator for six months with thirty insulator failures, or more than one a week.

Since re-insulating with insulators tested by the oscillatory transformer, we have operated for four months with no failures.

A. O. Austin: I would like Prof. Creighton to say a few words about the question of dielectric spark lag in flash-over on insulators of different sizes—the question of the ratio of puncture strength to the flash-over voltage is on a wrong basis on many of the insulators, so far as operation is concerned. An insulator of very large striking distance may have a comparatively low flash-over value, and may easily have a ratio of dielectric strength as based on oil tests, or any other test, of say, 2 to 1, and yet, so far as operating conditions go, this insulator may not be nearly as good as one having a ratio of 1-2 or 1-3, because the latter may have a short striking distance. That is the theory of the best operating types of insulators I know of today. It is of considerable economy and means much in the future development of the insulator along all lines of reliability under high-tension conditions or surging conditions.

P. W. Sothman: I do not believe that the high-frequency test will permit us to do away with all others in the testing of electrical porcelain. It will show us a certain number of failures, which would be discovered by the time-tests if they were continued for a sufficient length of time. It will show us a condition which may slip through some of the other tests. But there is a somewhat different point of view in the consideration of the insulator, and that is, we are trying to get a commercial piece of apparatus; and we have not been able yet to determine how electrical porcelain should be tested—should it withstand at the thickness of 1 mm. so many volts, or should it withstand a mechanical strain of so many pounds, applied in a certain form? If we take all our other electrical material, we find that it is pretty well standardized. You may say, we know that a piece of insulating cloth of a certain thickness should withstand a certain voltage and temperature.

Now, what are we doing with all our tests on insulators? They are absolutely arbitrary. We take the insulator and punish it until it is destroyed; and then we say it is good, or it is not good, just as we feel. But as long as we have no way to measure our static correctly, as long as we have to conduct our tests on phenomena which we do not master absolutely, that long we must take tests into account which will cover the whole electrical test; and not go on and say " I am making a high-frequency test, with the time duration specified, because I know it will either destroy or not destroy the insulator."

It has been shown that there are many insulators which hardly can be destroyed with high frequency, and still in operation they show up wonderfully. Where is the measurement? What may we expect from an insulator which is to be operated at 30,000 volts, and what should we ask the manufacturers to deliver? Is not the high-frequency test as we administer it far too severe? If it is too severe, I think the curve shown in Fig. 35, of Mr. Creighton's paper, shows us very well that there is a point at which we must stop; and I think that it is now up to us to find out where that point is.

In curves Figs. 19 and 20, I think Mr. Creighton shows us what we have talked over for a good many years, the variety which still exists in the electrical quality of porcelain. We are shown that porcelain will fail at a certain thickness under conditions for which even the manufacturer himself cannot find any reason. It was the same clay, it was the same feldspar, the same temperature and the same time process. Everything was the same. That is the point at which I think the operating engineer, especially, should work hand in hand with the manufacturer, to come to a real practical conclusion.

Mr. Austin shows that tests have been made during the manufacturing process. Should not far more tests be made during the process of manufacture—would not that eliminate lots of trouble? Mr. Creighton tells us that in the drying process a very high percentage of failures takes place. We may not have today ways and means of testing, but I think we should try to eliminate all failures before they are assembled and before they go far enough into the process of manufacture to make the cost of elimination unduly large.

Should we not adopt the rule that the test of the high-tension insulator be made in the unglazed shape? The glazing is such that the real dielectric effect is zero, whereas it still has an effect on the test. Glazing consists more or less of the metal oxides which change the apparent effect to a certain degree.

A closer termination or relation on the high frequency should be adopted. Mr. Creighton stated that between 60,000 and 300,000 volts is a big gap, whereas between 100,000 and 500,000 volts there is hardly a noticeable difference. Those are things which we should investigate more thoroughly. I would be thankful to Mr. Creighton if he would give us some more information, especially some reason why, on the lower frequency, this great difference is apparent.

On seeing the insulators which have failed on lines under actual operating conditions and comparing them with insulators failing under test conditions we notice a big difference. We find that the test conditions, as adopted now nearly uniformly, are not by any means the operating conditions. Many punctures in the high-frequency test have occurred on the outskirts of the umbrella, whereas in the ordinary way the insulators are punctured far closer to the center of the pin, or to the center of the wire. Mr. Austin made the remark that this form of puncture was due to the pin and wire, showing that these conditions certainly have a peculiar effect on the actual failure of the insulator.

I agree with Mr. Austin and Mr. Lawson, about the relationship between the flash-over and the puncture. That relationship must be very, very carefully considered. I am not absolutely convinced that such a relation of 1 to 2, between puncture and flash-over, is always the correct one. It may be correct under certain conditions.

Farley Osgood: We are quite happy with the results we are getting in New Jersey, but in justice to the insulator situation as a whole we would ask you not to forget that we are working with 13,000 volts normal. Our problems, to my mind, are probably quite different from the problems of those men who are operating at really high voltages. It occurs to me that while perhaps a 2 to 1 ratio is right for us, and our results seem to indicate that, yet, as Mr. Lawson said, we may be below the plane in all of our experimental work, about which Mr. Austin has been talking. In other words, our problem may be in an entirely different class. Therefore in our 13,000-volt work, while our methods have brought us the most satisfactory results, I do not think they can be used to determine the whole insulator problem. We do not want to lead anybody astray. We are simply giving our experiences with our own voltage.

L. L. Israel: For the last few months we have been engaged in the Navy Yard in Brooklyn in testing insulators for wireless work, and in these tests we found that the question of dielectric hysteresis in the material was of prime importance, that questions of accidental flaws were of secondary importance. In testing insulators for this purpose, we used as one of our means the method described by Mr. Creighton. In using that method with some variations in circuit arrangement, we found that the time of application, frequency of oscillations, the damping of wave trains and the spark discharge frequency are of prime importance in determining puncture value referred to sphere gap settings. In our work, however, we used wave trains which were probably much less damped than those obtained by Mr. Creighton. The breakdowns in most all cases were directly or indirectly due to the heating of the insulators, which heating depends upon all the factors enumerated above.

This leads me to state that it does not seem as though the tests developed by Mr. Creighton are very definite or conclusive, because in varying the frequency of oscillations as he probably did, he also probably varied the damping. We have found that higher frequency and lower damping may so neutralize their effects as to cause no variation in puncture value determined by sphere gap. Again, the effective value of the voltage applied to different insulators varies with the type of insulator that is put to test in the circuit shown by Mr.

Creighton, because the secondary of his transformer, and the insulator to be tested with its variable capacity and resistance, form an oscillatory circuit of variable frequency.

The effective value of applied voltage would vary considerably for different tests, depending on the ratio of frequency in this circuit to that in the exciting circuit. The effective value of applied voltage is also dependent upon the material of the spark gap used. A zinc gap would give a higher effective value than a copper or silver gap.

Mr. Creighton pointed out that if a blast of air is blown across the gap three discharges take place per alternation. The number of discharges that take place per alternation also depends on the voltage impressed on the power transformer, and on the resonance frequency of the low-frequency circuit. I am trying to point out some of the many important variables in this method of testing which, at first sight, do not seem to have been properly taken care of.

R. P. Jackson: Two methods have been proposed of obtaining a so-called high-frequency or impact test of porcelain. One method consists of a resonating circuit with a spark gap producing high-frequency oscillations, which are stepped up by means of a Tesla coil. The other method consists of charging an air condenser to a high voltage and discharging it over the insulator, producing an initial impact with successive oscillations.

Of the two methods, it is quite apparent that the Tesla coil scheme is more portable as it involves no high-voltage power transformer and the whole equipment can be put on a truck, which can be readily moved from place to place and is not so dangerous on the high side. On the other hand, any one possessing high-voltage testing transformers of sufficient voltage for his purpose can at a very moderate expense install the air condenser and spark gap necessary for the impact test. For that reason, it is a much simpler scheme for an operating man to install for temporary use in connection with any testing transformer or other high-voltage transformer which he may have available.

We have at East Pittsburgh carried out a series of comparative tests to determine the respective values of the Tesla coil scheme, the high-voltage impact scheme proposed by Mr. Percy Thomas and the test under oil at normal frequency, all as compared to the ordinary flash-over test at normal frequency. Our experiments so far indicate the following results:

Porcelain apparently punctures at practically the same voltage, regardless of the frequency employed. So far as is to be determined by spark-gap measurements, groups of porcelain of the same design and manufacture will puncture at the same voltage at 60 cycles under oil as they did by either of the so-called high-frequency methods. The voltage in each case was estimated by the sphere gap. There are essential differences, however, in the character of the test. When tested under oil, the puncture always occurs along the metallic electrodes and the stress does not appear to be spread out over the surface of the insulator. Either of the high-frequency methods, on the other hand, spreads the test out over all of the vulnerable points of the insulator.

At normal frequency in the air there is a fairly definite flash-over voltage for a given piece of porcelain, and no higher voltage can be impressed on such a piece. With either of the high-frequency methods, however, a very much higher voltage, in fact, an unlimited voltage can apparently be impressed on the porcelain. This, of course, is due to the suddenness with which the voltage appears, thereby preventing general ionization of the air, with constant breakdown of the air, as is the case at normal frequency. The virtue then of the high-frequency method consists primarily in the convenience with which a materially higher voltage can be impressed on the insulator at the place where test is wanted, than can be obtained with the normal frequency test in air.

It seems to be true, however, that reasonably good insulators that have passed the 60-cycle test will stand up for a very long period on a high-frequency test which does not flash over the insulator. In other words, a test which simply produces corona over the insulator does not appear to be materially more severe than the normal frequency test. It is only when the voltage is raised so that a potential value somewhere approaching the puncture value of the insulator is applied that the porcelains begin to fail. This failure begins by picking out the weaker ones, and as either the time of application or the potential applied is increased, more insulators fail.

The point just mentioned, that the length of time of application has much to do with the number of insulators broken down, indicates the most serious limitation of this method of testing. There appears to be no definite point in high-frequency testing at which we can say that such a group of insulators is bad and the rest good. A more severe test simply punctures more insulators. By severity, may be meant either long time of application or higher potential. This feature of length of time of application is a serious one, because it apparently indicates that the application of a high-frequency or impact test damages, to a certain extent, all the porcelain tested. The extent of this damage is, of course, such as to ruin the poorer pieces, and possibly it does not seriously impair the better pieces, provided the test is not continued too long at too high a voltage. For this reason, the test should be used rather sparingly, but not with the idea that all bad insulators can be weeded out and all the good ones left intact. Apparently the high-frequency methods of testing will, however, eliminate the very poorest material that has passed the 60-cycle flash-over test without very seriously damaging the better pieces, provided the test is not continued for more than a very short period. Just how long this period should be, is difficult to determine, and probably varies somewhat with the shape and size of the porcelain piece.

Our tests at East Pittsburgh do not indicate that it would be desirable to standardize either the Tesla coil test proposed by Mr. Creighton, or the impact test proposed by Mr. Thomas, at the expense of the other. There does not appear to be any material difference between them as to severity of test if properly handled. Either method, if so operated as to maintain a continuous stream of sparks over the insulator, will heat up the porcelain, where sparks continue in one place. Either method will materially damage the porcelain if continued too long at too high a voltage, and either method will search out weak spots throughout the area of the porcelain, because the sparks hug closely to the surface of the porcelain and tend to cover in succession the entire surface, whereas the 60-cycle test is limited in voltage to the flash-over point of the insulators, and the flash-over spark follows an air path over the edges of the petticoats, rather than over the surface of the porcelain.

We believe the test can be used to advantage in judging pieces of different manufacture as well as different designs of porcelain and we are inclined to believe that it can be used sparingly as a commercial test on material that will afterwards be subject to lightning. We do not believe, however, that the time is ripe for standardizing either method, but that the matter should be left at the present time with a simple statement that either scheme affords a searching test which will pick out the weaker porcelain with some slight damage to the remaining pieces. We should rely upon the accumulated experience of several years' service by insulators tested by these methods, rather than upon any immediate experience with the test. It will be desirable to continue tests by these methods, as undoubtedly they constitute a distinct advance in the determination of the quality of electrical porcelain.

I was recently endeavoring to formulate a specification of porcelain, and it became an important and a difficult thing to determine how much of this high frequency we should apply. Just as soon as we begin to weed out porcelain that has passed the 60-cycle test, the cost of which is based on the previous losses the porcelain factories have sustained, the question of price comes in. If we are going to increase their losses, they will have to charge more for it. Just how much are we willing to sacrifice in increasing the price of porcelain by weeding out the poorer ware, when there is no definite point, which we are sure of, when we can say, " this ought to be weeded out"? We do not want to go too far or too fast.

There are some later experiments which we have carried out that are of interest. We tried an impact test, employing a high-voltage condenser, discharging upon the porcelain, but developing the voltage by putting direct current through the low-tension side of the test transformer so that we would get one rise of voltage and one discharge from the insulator. The direct current was broken in small steps by inserting resistances so there would be no indeterminate surging in the broken circuit. It was arranged so that the direct current reversed through the transformer each time, to take up the residual flux that might be latent in the transformer. We got a severe test similar to Mr. Thomas's impact test, which he described a couple of years ago, except that it was with a definite number of impacts which could be counted. We arranged to get one a second. This test proved as severe as the ordinary alternating-current test, but no heating took place.

This test was then arranged with the impact always in the same direction by cutting out the reversal of voltage, but still killing the residual flux in the transformer, so we would get the same voltage. If the pin of the insulator were negative, and the voltage brought up to a certain point, the insulator would flash over 95 per cent of the times the voltage was applied; while if the pin of the insulator were positive, it would only flash over about five per cent of the time. In other words, with the pin negative, the tendency of the insulator to flash around the petticoats is materially increased over that with the pin positive. The fact that the pin was negative, even if it was the grounded end of the circuit, made it flash over. That is analogous to the well-known condition of the pin and a plate. If a high direct-current voltage is applied to a pin and a plate, the spark will pass much more readily if the pin or needle is negative.

Another curious thing which we have not entirely verified, but which appears to be true, is that if stress is applied in the same direction repeatedly by the method just described, the insulators seem to be able to sustain a great many impacts without suffering. As soon as we change the connections and begin to reverse the impact, first one way and then the other, the insulator fails quickly.

That is the effect we get on any of the higher frequency methods. That leads to the conception that there is apparently some residual molecular stress that lasts an appreciable time after the main stress is applied. Owing to a similar stress in the same direction a few seconds later the torque or the resistant power is already braced to receive it, and the insulator stands. If we apply the test so it reverses the molecular stress the insulator fails.

P. W. Sothman: We should by all means agree on one point, and that is, when our actual operating voltage is 30,000 volts, as Mr. Austin has on his line, that the line conditions are closer to 20,0000 than to 30,000. We know that we can build something which will stand 30,000 volts, but should not the insulator withstand 20,000 volts with the same safety that it would withstand the 30,000? Should not the test voltage and the test specified be based upon the actual line conditions?—and not on the assumption that we are running at 30,000 volts, because they actually do not run at 30,000 volts. That is only the apparent voltage, otherwise we could not have the failures that we find today.

Farley Osgood: I think perhaps I did not quite bring out the point in the manner I wished. Because of the fact that our operating voltage is 13,000, and that our porcelains are, therefore, quite small, I feel we may get surges which are greater, proportionally to our normal conditions, especially as we have a good deal of cable in connection with our lines, than is the case when you are considering the laying out of systems to be operated at 60,000 to 100,000 volts. I think our disturbances are out of proportion to the size of our porcelains, as compared to the high voltages. Therefore, I make the precautionary statement that this problem of the porcelain cannot be determined on the requirements of our low voltage. We do not want to mislead any one, but mention what we are doing as a matter of progress.

William H. Jacobi: I want to say a few words on this matter of porcelain insulators from the point of view of the designer and manufacturer who through their experience, are necessarily the ultimate to render a verdict on the usefulness and limitations of porcelain such as we electrical engineers want for our purposes. When we are called upon to get up purchasing specifications for insulators, we demand that porcelain shall be thus and so, shall stand this and that other test, etc. Little do we concern ourselves as to what means or processes the producer has to resort to, to obtain the goods we demand, and then at a low price, because of the competition of the other fellow who tells us that through his "patented processes" "most modern equipment" etc., he can give us all we desire.

We all know of the relation that the internal resistance of materials bears to externally applied forces from whatever source, mechanical, thermal or electrical, and I hold that, while porcelain is of different nature from most other materials which have been made use of in engineering construction, it is not free from being subject to the effects and laws governing other materials which undergo similar manufacturing processes. The axiom that the internal resistance of materials shall at least overcome the externally applied forces, needs no proof. That the internal resistance of any material depends upon its physical structure, and in turn its physical structure depends not only on the composing ingredients but largely on the methods adopted for treating these ingredients, is nothing new. Yet, to the observing eye it would seem that the field of research in the matter of electrical porcelain has been one-sided. Many manufacturers have gone far and wide in the art of blending ingredients, believing that therein lay the secret of producing porcelain of the qualities required for electrical purposes. While no doubt the ingredients required play a very important part in the makeup of the finished composite material, in the case of porcelain, with a proper design and skilled firing, the matter of proportions of ingredients may be assumed as being governed largely by economical considerations in manufacturing. We have heard very little in the way of proportions and shapes and thermo-mechanical effects to form a measure of judgment on the merits of porcelain insulators, particularly for high-tension power transmission service, and I desire to emphasize two points in this connection. One is the shape and proportions to be given the mass of porcelain material, so that when it has undergone a given firing process it shall be free of internal stresses. The other is the dimensional proportions to be given the insulator to resist the required values of flash-over and puncturing voltages.

I had the opportunity, some months ago, of observing the insulators for a certain transmission line, before and after service. It was quite singular to note that the greater number of fractures were very much alike in extent and location, both before and after service. Close examination of the broken surface revealed that some portions exhibited a glassy appearance while other portions were dull, and that this condition was more or less uniform. My explanation in this case is that the glassy portions, which were visibly thinner, reached the vitrifying stage before the portions that were dull, thereby changing the physical structure between these portions and setting up stresses of such magnitude as to require relatively little effort, whether mechanical, thermal or electrical, to cause breakage.

The idea of initial internal stresses in porcelain, particularly in view of the experience just mentioned, led me to inquire into their cause and remedy. Naturally any material which is free from internal stresses, when used, will place at our command not only its entire store of internal resistance to react on externally applied forces, but, in the case of porcelain, will possess in its texture other desirable qualities for electrical purposes. My conclusion is that porcelain, not unlike other materials undergoing similar processes in their manufacture, is subject to the same laws observed in casting metals. To illustrate: if we take a cast iron disk of rectangular cross-section, malleabilize it, and break it in halves, the cross-section will exhibit two distinct areas. One is of varying texture that grades down from the surface, fading away into the other area, which is very uniform in texture and appearance. The area of varying texture represents the mass around the disk which is exposed to quicker impregnation of moisture, dehydration, heat absorption and heat dissipation. The area of uniform texture is affected more slowly and uniformly by those agencies. Brick, tile, a loaf of bread, etc., exhibit visibly these effects.

We can now appreciate that, due to the greater ratio of expansion and contraction in this outer portion, stresses of varying degree are present in the section which decrease or destroy the internal resistance of the material. The problem of obtaining a piece of material of this character, free of internal stresses, will be solved by merely avoiding the presence of that portion of varying texture, and by utilizing that portion of uniform texture. In shape this latter part varies according to the geometric proportions of the mass; the theory on this point is that it is subject to the law of the parabola, otherwise commonly known as the law of the squares.

The basic shape of disks such as are used for insulators should therefore be a flat paraboloid, and theoretically this is the shape that should be given to edges of metal castings; however, the ductility in metals makes it unnecessary to give castings these more difficult curves and suitable radii are satisfactory enough. In the case of porcelain, which is devoid of ductility, it would seem that that law should be adhered to, and I believe that the paraboloid shape should be made to constitute a point of judgment on the merits of design of insulators.

Arbitrarily selected radii as are found in the outline of most insulators may contain portions of the varying texture area just referred to and thereby introduce chances of creating undesirable initial internal stresses.

From the foregoing considerations bearing on the internal stresses set in the mass of insulators by improper design, it is very gratifying to observe that the multi-petticoat disks of earlier designs are giving way to smooth disks of the more logical forms; as an example, the insulators developed for the Chilean Exploration Company, recently described in the *Electrical World* by Mr. P. H. Thomas, may be cited.

We have at some time or other been informed that certain insulators which have given satisfactory service on 66 kv. have failed when put on 44-kv. service. After the admirable research carried through by some of our colleagues, we may find a number of satisfactory explanations and blame local conditions, wave shape, altitude, etc. These explanations, as good as they are, do not tell us how to guard against such failure. In this connection I call your attention to the second point I desired to emphasize, viz., the dimensional proportions to be given an insulator for a particular service.

In so far as the present stage of the art is concerned, and assuming that we have mastered the science of shaping insulators to render them free of internal stresses, a given mass of porcelain material can be so dimensioned, other things being equal, that for a constant and definite flash-over voltage, it may be made to assume a variable resistance against puncture, the maximum value of which is that of flash-over. Conversely, the same mass of porcelain material can be dimensioned to offer resistance against puncture by a voltage of constant and definite value and, within certain limits, be made to offer a variable resistance to flash-over voltage, the minimum value of which is that of the puncture voltage.

In view of these facts, I feel that we ought to have a common measure by which to judge the merits of flash-over and puncturing voltage ratios applying to porcelain insulators.

By construction, pin insulators possess high resistance to puncture and a low resistance to flash-over, a condition regarded as desirable nowadays— yet, I have seen pin insulators which, having failed by puncture, did not give evidence of surface spill. Probably mechanical defects of the internal stress order, or the presence of carbonized organic matter, or other causes were responsible for the damage. This train of assumptions does not satisfy the mind athirst for knowledge. In the case of suspension insulators, on account of the intermetallic linkage we are not prepared to say anything final and definite. Some of us are in position to arrive at some logical conclusions that may constitute points of judgment on insulators, or rely on results and content ourselves by saying that because a certain insulator has not given trouble, that is "the insulator."

I can conceive characteristic curves bearing on the "*proper proportions*" for insulators, like Fig. 7.

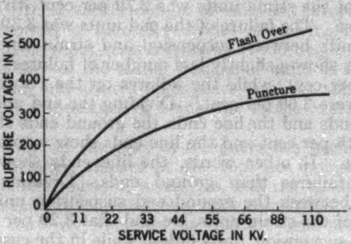

Fig. 7

I can further conceive a similar set of curves giving higher or lower values applying to high and low altitudes; also to high and low frequencies, and probably bearing reference to the effects of wave shapes. The task involved in obtaining these data, evolved in such channels of experience and judgment as to make them worthy of becoming a standard measure of the merits of porcelain insulators, is necessarily vast. Probably, no one of us could gather in his lifetime all that knowledge, but we engineers fond of standards to measure our accomplishments and limitations must have such a standard.

Progressive manufacturers of electrical porcelain realizing the import attached to their product, are carrying on exhaustive research and testing along the lines indicated, and in justice to ourselves we must cooperate with them to get the missing link.

Julian Cleveland Smith: The discussion this afternoon has rather drifted away somewhat from the point I thought it might hinge upon, and these figures which I will give you are not very apropos of anything that has been discussed the latter part of the afternoon. During the last two years we have carried out a series of tests on one of our high-tension lines involving about 50,000 disk type insulators. These are of an old design now, a design which has been materially improved, and tests on the new designs show the performance is very much better than on the first design. It is quite interesting, however, to see how the losses shown by these tests are distributed. The line has been in operation for about three years; there are 48,000 units covered by these tests, of which 37,800 are suspension units and 9000 are strain units. There are about 10,800 of the suspension units under the heading of end units, which includes both ends of the string, and 2400 of the strain units, making the total number of end units 13,200.

The total number of failures in all of this number of units during the operation of the line up to last fall was 2.58 per cent. The failure of the suspension units alone was 2.47 per cent. The failure of the strain units was 2.79 per cent, that is, a very slight increase. The failure of the end units was 3.39. Dividing these end units between suspension and strain units, the suspension units show a slightly less number of failures, the failures being 3.25 per cent, while the failures on the two ends of the strain unit were 3.69 per cent. Dividing the end units between the ground ends and the line ends, the ground ends show a total failure of 3.15 per cent and the line ends show a total failure of 3.63 per cent. In other words, the line ends show a greater number of failures than ground ends. Dividing up these units again between the ground end suspension units and the ground end of the strain units, we find that 3.29 per cent of the ground end suspension units failed, while in the case of ground end strain units there were only 2.83 per cent which failed. The line end suspension units failed to the extent of 3.22 per cent, while the heaviest failure of all was in the line end of the strain units, amounting to 4.56 per cent.

The other units, exclusive of the ends, were 2.27 per cent, and dividing these again, the suspension units showed 2.16 per cent, and the strain units 2.49 per cent.

The net results of these figures seem to indicate, so far as our type of construction is concerned, that there is a slightly increased percentage of loss in the strain units. It also indicates that of the units which failed the end units are more apt to fail than the intermediate ones, and there is a slightly increased tendency to fail on the line end. The work was done in two successive years, and I have not divided it up at all, and it indicates this—that there was a considerably greater number of failures found during the first year, as against the second year, which shows that, while there was an apparent constant further development of failures, the first test located a considerable number of these faults, which no doubt existed at the time the line was put up.

It has also developed in these tests that a very high percentage of these failures is due to what may be termed mechanical troubles, that is, cleavage planes in the porcelain, and defects which are so evident that the men making the tests can by simply looking at the insulators determine how the insulators fail.

The various methods of test, so far as our own work is concerned, do not seem to have developed any great benefit from the high-frequency tests. We have an apparatus similar to that described by Prof. Creighton, but as applied to these particular units there does not seem to be any more likelihood of failure with high frequency than with low frequency.

We reproduced in our laboratory typical failures that existed in the line as regards the mechanical failures of these particular units. The mechanical failures, due to thermal stress, cleavage planes, or moisture, or some cause of that sort, are much more difficult to reproduce, except those due to temperature. By taking any of these earlier designs of units and carrying them up through a number of successive cycles of varying temperature, say varying from room temperature up to 150 deg. cent., you can cause almost any of the earlier designs of units to fail, and the failure is equal, and always takes place in about the same plane and has every appearance of being due to the expansion of the cap.

The tendency on the part of designers has been to produce a porcelain heavier, thicker at the top, less points of attachment to the metal parts of insulators, and the result has been a very material improvement. We made some tests on the newer type, and I may say, so far as the thermal tests are concerned, we find that the new type insulators are practically immune from any ordinary thermal failures, that is, you have to carry the temperature so high, and over a considerable number of cycles, that the failures due to this cause in ordinary operation would probably be very small indeed.

One other point of some interest is this—that the failures, 50 per cent of them, caused by the so-called mechanical troubles, were those things that probably occurred in the factory, and were not deemed essential to the design of the insulator, and are pretty well scattered all over the lot. You could not say that they are located in any one particular place. On the other hand, the other fifty per cent, due to high frequency, or high voltage, or a combination of these two, are so located that it would be hard to explain them by any probability law. They are in the zones of lightning disturbance, and occur in those places where the disturbances are known as taking place, that is, they are bunched together, and there will be long stretches of line, twenty miles or so, in which there is a very small number of failures, and then will come a few miles in which there is a large number of failures.

I want to close this discussion by simply saying that, considering everything, the number of failures is very small, indeed, especially when we remember this particular line has been in operation for over three years and that no whole string of insulators has failed, that there has been no failure, in other words, due to the breakdown of the insulation caused by flash-over of an entire group. It may be considered that the fact that we have picked out by tests such a small number as only 2.5 per cent, is a rather good record, and particularly so when you consider this is one of the earlier designs of insulators.

Harris J. Ryan (by letter): We are much indebted to Professor Creighton for placing before us the essentials of the art of high-voltage porcelain production and for his efforts to establish a standard high-voltage porcelain test.

Plenty of energy, though not too much, must be applied to the porcelain insulator at high voltage to locate and develop electrical faults. Otherwise, as with the megger test, only a limited class of faults can be located. *For standard test* purposes the energy applied to the fault so as to produce failure at 60 cycles, sustained sine wave voltage, is too little, while at 200,000 cycles or 3333 times 60 cycles, sustained sine wave voltage, the energy is correspondingly too great. The failure and conduction of the air, or the conduction of the gas when oil-immersed, in touch with the porcelain at the fault or the region to be ruptured, is largely the means for applying the energy which starts the localization of the fault or that sets up thermionic conduction and puncture. The power factor of a capacity charging current when passing a zone of conducting air in a particular case at 60 cycles was found to be about four times what it was correspondingly at 180,000 cycles. Since the value of the high-frequency current was 3000 times the value of the 60-cycle current, the energy used in conveying the 180,000-cycle current across the conducting zone of air was about 750 times the energy required correspondingly at 60 cycles. The Creighton oscillator applies to the test specimen normally 120 high-voltage damped wave trains per second. The life of each train is short compared with the interval between succeeding trains in which no energy is applied. Herein there is a great advantage for a standard test. The power applied is high during the damped high frequency voltage impulses. Thermionic conduction is started at the fault; it is started also at other points where the porcelain is sound. The action is greater at the fault than elsewhere. The interval of rest between wave trains is sufficient for ionization and heating to disappear at all points established, except at the fault or at points between which puncture must occur. Succeeding wave trains, while continuing to pour energy into the fault, do not pour it in upon the former routes of conduction to the sound porcelain. Such routes being acquired by accident are not, in general, reestablished. Herein is essentially the difference between the oscillator and the sustained high-frequency tests. In the sustained high-frequency test the slightest overstress of the atmosphere adjacent to sound porcelain will result in the formation of a conducting air channel that will be sustained.

It appears that our electrical knowledge and facilities for high-voltage porcelain insulator production and use are now far in advance of our mechanical knowledge and expediency. On the mechanical side of the art very little has been done. On the surface it would seem that important things to know are: How long should units made up of porcelain, iron and cement, be allowed to age after having passed the regular factory tests? What physical treatment should they be given in the aging interval? What tests should they be given before being placed in service? Deeper down, this question appears: Are present designs, from a mechanical-electrical standpoint, the best that can be had in regard to aging quality?

Thus by using 20 kv. sustained at 200,000 cycles, a sound suspension type insulator unit may be punctured that would endure 90 kv., 60 cycles, producing flash-over.* While the sustained high-frequency test has little or no value for routine purposes it will doubtless be of great value for determining useful facts in regard to new and old designs.

The super-spark potential test with the Creighton oscillator promises to be of high value. In this test the porcelain is subject to an intense and highly localized thermionic conduction which brings about puncture by fracture or by fusion and spark blast. With the aid of this test designs may be possibly produced that will exhibit marked improvement in ability to endure punishment of the sort that is developed by lightning discharges.

J. S. Lapp: By high-frequency testing we seem to develop entirely new characteristics of dielectrics. The commercial and investigative testing with high frequency with which I am intimately acquainted has not been carried far enough for substantial conclusions. Results so far seem to indicate that high-frequency testing will not appreciably increase the cost of insulators. Fifteen years of field experience on pin type insulators, with support grounded and ungrounded, together with six or seven years experience with suspension construction, nearly always with dead ground at the insulator, seem to be urging the insulator manufacturer toward a safety factor in insulators, that roughly coincides with that indicated by high-frequency testing.

The principal value of high-frequency tests seems to be for purpose of design and not a commercial selective test. As a commercial selective test, high frequency may, depending on the thoroughness of the normal frequency test and design and material of insulator, select out from 1/10 per cent to 2 per cent defective

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*For the results of tests of this sort made upon eight units see "Sporadic Insulator Troubles," by Harris J. Ryan, read at a meeting of the San Francisco Section of the A. I. E. E. and published in the *Journal of Electricity, Power and Gas*, Vol. XXXIV, Feb. 27, 1915.

pieces, but it will be found that most of the defects are at the edges of the shells where the voltage drop through the shell is very slight on normal frequency. High-frequency testing does not appear to be more efficacious than, if indeed equal to, normal frequency testing for purposes of selecting out immature or under-vitrified porcelain. We ordinarily test 100 to 200 insulators at a time in one circuit with insulators flashing over and the kick and energy for destruction by puncture of this large capacity is a most valuable selective test which will not quickly be superseded by a high-frequency test. A high-frequency routine commercial test on each insulator appears needless if materials and thickness of shells are such as to pass design tests. In short, the expense of weeding out from 1/10 per cent to 2 per cent on high-frequency test may be justified by increased line security, but this test will probably be added to and not supersede our present methods of normal frequency lag test.

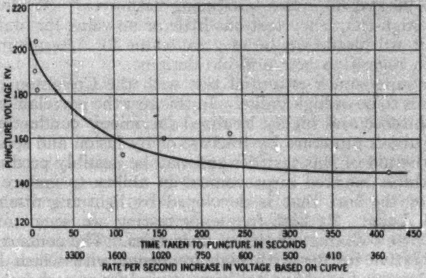

FIG. 8

We cannot predict that this 1/10 per cent to 2 per cent selected out after normal frequency test will eliminate an equal percentage of line insulator troubles. Nor, in the absence of more exact knowledge of what the line phenomena are, can we now judge how severely we should test at the factory—that is, how nearly we should in testing approach the critical strength of the insulator.

High-frequency testing is positively dangerous until we have established safe standards. Thus we can subject a sheet of porcelain say 5/8 in. thick to a voltage of 85,000 at 200,000 cycles and puncture the piece, after which it will withstand, in many cases, 100,000 volts at normal frequency for an appreciable length of time, or we can, by immersion in oil, literally bore holes into porcelain at each terminal without puncture. The holes are roughly semi-spherical and evidently produced by local heating which splits or spalts off pieces of porcelain varying in size from dust up to pin head.

High-frequency puncturing is peculiar. Thus, with normal frequency a puncture results in a comparatively large thread of glass (fused porcelain), whereas high-frequency puncture results in many discharge paths or fissures. After puncture actually occurs, when testing in oil, carbon is deposited throughout these cracks. If, however, bombardment is not carried to puncture voltage there is no evidence of carbon deposits in the body of porcelain, although distinct fissures or hollows in the intact body are discernible with the microscope and these appear as if the porcelain had undergone a digesting or honeycombing. The excessive heating causes long extended cracks in glass when punctured, and with the glassy, highly vitrified best European porcelain similar cracking occurs.

As to manner of applying high-frequency test, it appears that the puncture strength of porcelain depends more upon a critical voltage gradient than on time of application. Fairly exact determinations demand more exhaustive tests than we have yet been able to make, but roughly it seems that a test for one minute would detect defects, indeed twenty seconds may appear unduly conservative perhaps, but would, it is believed, serve in nearly all cases.

High-frequency testing has already given a great impetus to improvement in porcelain as a safe dielectric. Since it appears that the destructiveness of high-frequency tests results from excessive local heating, a very tenacious material should be provided. Glass or glassy porcelain, because of its small thermal accommodation, cracks and current follows through before the bombardment has an opportunity of digesting or boring into its structure. Best porcelain will withstand semi-destruction or digesting before giving way to open puncture. The internal crystalline structure of porcelain is complex. It has to do with the pyrochemistry of silicates, which has not yet been written and only slightly investigated. The methods of the high-voltage porcelain maker are therefore highly empirical, and his particular experience highly valuable. Thus, each maker must for his special porcelain ascertain a thorough knowledge of the workability of his clay mixture—the limit of abuse—and the best burning methods. As a concrete instance, a manufacturer may have for years burned his porcelain for so long a time that he held it dangerously long in the crystallizing temperature zone for that mixture. He called it the "soaking heat" and sincerely intended to add quality. Structurally the product was weakened and on high-frequency test must fail by virtue of a weak crystalline bond giving way, shown by branching or tree-like permeation. Pyrometer tubes subject to continuous high heat sometimes undergo this crystallizing or devitrification and crumble or break.

At the other extreme is immature or under-vitrified porcelain. The process of burning porcelain, in addition to the complex silica reactions, is really an arrested reaction, the accuracy of which depends upon the personal skill involved. The most ambitious technician has but two tools to guide him over the delicate step—pyrometric cones, which are intended to measure heat, and trials for progressive shrinkage. Soft porcelain is very hard to detect and the greatest promise seems to be offered by a measurement of insulation resistance at very high potential to detect variations.

Conceive of a hundred grades of porcelain in one kiln varying in minute degree, some so near maturity that their structure can be conceived as a maze of capillary openings so small that they demand their own time for absorption—maybe a month; maybe two years. This is impossible to detect at the factory by any present method.

As interest in overcoming line insulator failure becomes keener, when insulators are bought as a specialized and highly technical product and standards are approached, some time the maker and purchaser may cooperate and make the porcelain far ahead of demand so that a period of weathering—say a year or more—will eliminate a great percentage of questionable material before erection.

Such qualities can surely explain some of our "fatigue" so-called, in insulators no less than in tableware; and the insulator maker of repute should be the peer at least of the high-grade dish porcelain maker in ability and product. Or is that too much to expect when high-voltage porcelain is hammered down to 4 cents per pound, whereas the dish maker would starve on 5 cents per pound?

Presented at the 305th meeting of the American Institute of Electrical Engineers, New York, March 12, 1915.

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FIXATION OF ATMOSPHERIC NITROGEN

BY LELAND L. SUMMERS

Abstract of Paper

The nitrogen contained in the atmosphere is in an inert form and does not readily lend itself to chemical reactions. To overcome this is the province of "nitrogen fixation."

There are very definite commercial limitations involved in accomplishing this, as the world's supply of nitrogen has been readily obtained from vast natural deposits of sodium nitrate in Peru and Chile and the production of a substitute must be at a competitive cost.

The electrical processes for fixing nitrogen have a very low efficiency, due to utilizing thermal energy only.

Combinations of electrical and chemical methods promise the most important developments.

Comparative figures are given showing amount of energy necessary per kilogram of nitrogen fixed, and the general economics of the subject is discussed.

I. Introductory

In 1898 Sir William Crookes, in his address as president of the British Association, very forcibly pointed out that the commercial fixation of atmospheric nitrogen was one of the greatest discoveries awaiting the ingenuity of chemists. He emphasized with very interesting figures its important practical bearing on the future welfare and happiness of the civilized races. This address brought forcibly to the attention of engineers the fact that the existing sources of fixed nitrogen were limited, and greatly stimulated the efforts of investigators. The problem itself had been worked on for over a century, as it was known that nature fixed nitrogen of the atmosphere by means of electric discharges, and Cavendish in 1781 had shown that a small amount of nitrogen was converted into nitric acid in the combustion of hydrogen with oxygen to form water, while Bunsen in 1877 obtained favorable yields by means of gaseous explosions. The earlier efforts commercially in the art were, however, largely confined to the fixation of nitrogen for the purpose of manufacturing cyanides, and the earlier bibliography of the subject therefore deals almost entirely with these efforts.

Commercial Products of Nitrogen. The three fundamental commercial products formed by nitrogen are, first, its union with oxygen to form nitrates NO_3 and nitrites NO_2. Second, its union with carbon to form cyanogen C_2N_2 and producing cyanides XCN and cyanamides XCN_2. Third, its union with hydrogen to form ammonia, NH_3. From all of the above products there are obtained many derivatives used in the chemical arts.

The most important of all commercial products are the unions of nitrogen with oxygen forming the nitric acid salts of commerce. These are of particular importance on account of the vast natural deposits of nitrate of sodium occurring in Peru and Chile, commonly called Chile saltpeter. Practically, this commodity is the one that sets the price for all other compounds of nitrogen, as it has been mined in Chile since 1830, and during the past 25 years its production has assumed vast proportions, the present annual output amounting to about 2,500,000 tons. This deposit of Chile appeared inexhaustible and therefore there was no occasion for alarm regarding the world's supply of combined nitrogen, but after years spent in exploration work it began to appear that the Chilean deposits would be exhausted before the end of the present century, and since then all other sources of combined nitrogen have received attention.

While there are a few scattered natural deposits other than those in Chile, there is none which has at the present time a chance of competing, most of them being of limited extent and situated in inaccessible regions. In Chile the deposits are easily worked and even after years of careless mining with no effort to effect economies, the present cost of producing nitrate is not excessive, varying from $10 to $20 per ton and selling in Liverpool for about $45 per ton. This leaves a profit of from $5 to $10 a ton on the operation after paying the Government of Chile an export tax of about $12.25 per ton. In the past 30 years this export tax has netted the Chilean Government about $500,000,000. Of the total production of Chile the United States imports about 600,000 to 700,000 tons per annum, the balance being practically all shipped to European countries. Chile saltpeter has sold as high as $60 a ton, but since 1909, when the agreement among the producers expired, the price has approximated $45 per ton f.o.b. Liverpool, making a price of from $35 to $40 per ton f.o.b. Chile.

The union of nitrogen and carbon to form cyanides and with hydrogen to form ammonia are two of the earliest forms in which the combined nitrogen was utilized. Most all animal and vegetable refuse contains ammonia compounds and these were the early sources of ammonia, and animal refuse products such as hides, hoofs and horns were the sources of combined carbon products forming the cyanides. Until the discovery of the McArthur-Forrest process for gold extraction, the markets for cyanides were comparatively limited and there was no great effort made to produce them on a large scale. With the rapid development of this art in the recovery of the low-grade gold deposits a sudden impetus was given to the cyanide industry, and large quantities of cyanides are now manufactured from ammonia and metallic sodium. Small amounts of cyanides for industrial purposes are recovered from the gas retort houses, but these processes are not generally applied and no particular effort has been made to extend the processes to the recovery of cyanides from by-product coke ovens. The greater portion of the cyanides is manufactured in England and Germany and some 20,000 tons per annum are exported annually by these two countries. As the cyanides of sodium and potassium for gold recovery purposes sell from $300 to $400 per ton, they represent one of the highest prices of nitrogen directly combined with a simple element.

The third great commodity of commerce, ammonia, is utilized extensively in industrial arts but in addition has been used for many years as a fertilizer. The annual production of sulphate of ammonia now amounts to about 1,250,000 tons and the Liverpool price approximates that of sodium nitrate, varying from $45 to $60 per ton. Practically all of this sulphate of ammonia is manufactured from coal distillation either from gas house retorts or by-product coke ovens, up to the past year there having been practically no process in operation for the direct synthesis of ammonia from its compounds.

All the older retort processes for the manufacture of gas recover ammonia by washing the illuminating gas with water. All by-product coke ovens likewise treat the by-product gas for the recovery of ammonia. American coals run from 0.9 per cent to 1.4 per cent nitrogen or from 18 to 28 lb. (8.1 to 12.7 kg.) of nitrogen per ton of coal. In the distillation of this coal about 20 per cent of the nitrogen is recovered from the gases of distillation, so that from 4½ to 7 lb. (2.1 to 3.2 kg.) of ammonia are recovered per ton of coal distilled; this ammonia when united with sulphuric acid forms sulphate of ammonia, giving a yield of from 18 to 28 lb. (8.1 to 12.7 kg.) of sulphate of ammonia per ton of coal distilled. Weak solutions of ammonia water are concentrated from the gas house retorts and the ammonia distilled from this water by breaking down the ammonia contents with lime, the pure ammonia then being united with sulphuric acid. In many of the coke oven plants the sulphate is formed directly by passing the gases into sulphuric acid, forming the ammonia sulphate by a direct process.

In general it costs about $15 per ton of ammonia sulphate to manufacture the sulphate from the ammonia, so that if ammonia sulphate is selling for $45 per ton, $15 of this is represented in the cost of sulphuric acid and the manufacturing, making the net ammonia cost with profit $30 per ton of sulphate, or, as the nitrogen content of the sulphate amounts to 21 per cent, the nitrogen represents an actual value of 7 cents per pound. With the great increase in the number of by-product coke ovens, there has been a greatly increased quantity of ammonia sulphate manufactured, and it would seem that under these conditions the price of ammonia sulphate will tend to diminish rather than to increase. The actual cost to the by-product coke oven plants recovering the ammonia, in addition to the $15 for manufacturing the sulphate of ammonia, will approximate $10 per ton, and if there is any profit to be obtained from the sale of ammonia, they can afford to recover it at this figure.

Another source of ammonia by coal distillation is from producer gas generated on what is known as the Mond system. In this process steam is admitted to the producer in excess, so that the temperature is not permitted to rise to a point where the ammonia liberated by the fuel is decomposed. This excess of steam tends to protect the ammonia and it is recovered from the producer gas by washing. In this process not only the ammonia carried in the volatile products is recovered but also a large percentage which ordinarily remains in the carbonaceous residue of the coke oven and gas house retort. As ordinarily distilled, about 50 per cent of the total ammonia of the coal remains in the coke residue and is not recovered. In the producer where this coke is consumed in the presence of steam the total percentage of recovery may be as high as 75 per cent of the theoretical nitrogen contained in the coal, so that from 15 to 20 lb. (6.8 to 9.1 kg.) of nitrogen may be recovered, or in terms of ammonia sulphate, from 60 to 80 lb. (27.2 to 36.2 kg.) of ammonia sulphate may be obtained per ton of coal consumed in the producer.

This type of producer has not been extensively utilized in America, as the expense of installation is increased by the necessity of washing a very large volume of low-grade gas, the volume of gas per ton of coal consumed in the producer being about 130,000 cu. ft. against about 10,000 cu. ft. per ton of coal as distilled in the coke oven.

A number of these plants have been installed in England and on the continent, but the aggregate of the ammonia sulphate produced is not large as compared to that from coke ovens and gas house retorts.

Available Nitrogen in Commercial Products. The question of the available nitrogen in the various compounds has in a measure determined the price of the product, the utilization in the fertilizer art being practically the basis of fixing the price. For a number of years it has been assumed that the selling price of combined nitrogen would be from 12 cents to 13 cents a pound. Thus Chile saltpeter, being about 95 per cent pure nitrate of soda, would have a theoretical nitrogen content of about 16.5 per cent, or, corrected for impurities, would have about 15.5 per cent nitrogen.

As the cyanides until recently were not used directly in the fertilizer art and were combined with more expensive products, their price has not been regulated by their content of combined nitrogen. The ammonia used in the fertilizer art is almost entirely used as sulphate of ammonia, on account of the cheapness of the commercial sulphuric acid and the ease of manufacture, and this product would therefore have a theoretical content of 21 per cent of nitrogen.

The above nitrogen products may be considered the fundamental commercial forms in which combined nitrogen enters the market, and while the fertilizer industry fixes the price of combined nitrogen, it is only one of the many industries in which vast quantities of nitrogen are utilized. Thus about 50 per cent of all the Chile saltpeter imported in this country is used in the manufacture of explosives, while an additional 25 per cent is utilized in the arts requiring nitric acid. Of the ammonia sulphate, a very large percentage is used directly as fertilizer, though there is a very considerable demand for use in chemical industries and such commercial applications as anhydrous and aqueous ammonia used in the refrigeration art. Practically all explosives have utilized nitrogen compounds as a principal ingredient, the earlier black gunpowder having used Chile saltpeter, charcoal and sulphur, and the later so-called smokeless powder utilizes the oxygen-carrying property of nitrogen as well as the inherent molecular energy in the production of such high explosives as nitroglycerin, cordite, lyddite, melinite, guncotton and various other nitrocellulose compounds, and modified explosives used in industrial work, such as dynamite and various blasting powders.

Fixation Processes. In considering the fixation of atmospheric nitrogen from a commercial standpoint, the limitations will be imposed by the selling price of the natural product from Chile, covering nitrate compounds, and the selling price of ammonia sulphate as obtained from coal distillation, affected as these prices will be by the manufacture of ammonia from atmospheric nitrogen.

In competition with the above sources of nitrogen there has been the constant effort toward the fixation or rather the utilization of some of the vast quantity of atmospheric nitrogen surrounding us.

A list of these fixation processes would contain the names of hundreds of investigators, and from the past twenty years of effort there may develop processes which at present are still experimental; but of the various processes which have reached the state of commercial application there appear to be four distinct lines of development.

First. The production of nitric acid directly from the atmosphere by means of the electric arc. In this process the nitrogen of the atmosphere is directly combined with its accompanying oxygen without utilizing any other chemical substances, the process consisting essentially of a powerful arc furnace through which air is forced, causing at this high temperature the nitrogen to combine with the oxygen, forming nitric oxide, NO.

Second. Methods of fixing nitrogen by means of electric furnaces or combustion where the energy of chemical combination is utilized, causing the nitrogen to combine with some substance with which there is a pronounced energy of chemical combination. These processes include furnaces utilizing calcium carbide, with which nitrogen readily combines to form calcium cyanamide, $CaCN_2$, and various processes for making combinations of nitrogen and a basic or alkaline earth metal such as calcium nitride, Ca_3N_2, or magnesium nitride, Mg_3N_2, or aluminum nitride, AlN, the chemical action usually forming a nitride or carbo-nitride.

Third. Processes for producing ammonia, NH_3, directly from nitrogen and hydrogen. These include the effort to use the various forms of electric discharge by which the nitrogen molecule may be decomposed and in the presence of hydrogen, form ammonia. As ammonia decomposes at a very low temperature (500 to 1000 deg. cent.) only the silent discharge seems available, and the yields are not commercial. The most promising of all direct ammonia processes seems to be that of Haber. In this process, a catalytic agent is used and under a heavy pressure the nitrogen molecule is decomposed and united to the hydrogen, thus forming ammonia. Salts of uranium seem to be preferred as the catalytic agent and have the power of acting on nitrogen at a temperature of about 500 deg. cent.

Fourth. Production of a high temperature by combustion, either utilizing catalytic agents or simply by producing a high temperature by means of the explosion or combustion of gases, directly combining the nitrogen and oxygen to form nitric oxide, NO. This method, early used by Bunsen in the combustion of hydrogen to form water, has been applied to coke oven gases by Hausser. A bomb is used and the mixture of gas and air is fixed electrically; the small amount of NO formed is recovered and converted into nitric acid, HNO_3.

The chemical form in which the commercial supplies of combined nitrogen appear on the market is due largely to existing commercial conditions. The nitric acid combined as sodium nitrate occurs in this form simply on account of being naturally produced in this form. The ammonia appears on the market as ammonia sulphate largely on account of the cheapness with which sulphuric acid can be obtained, and the widely distributed plants for its manufacture, making it one of the cheapest and most convenient forms of combining with ammonia. It is probable that in commercial nitrogen-fixing plants, if both ammonia and nitric acid are manufactured, one of the most convenient forms for marketing this product will be by using nitric acid in place of sulphuric acid, making ammonia nitrate, NO_3NH_4. This product is on the market at present but is only manufactured from sodium nitrate and from ammonia, or in some of the plants where nitric acid is manufactured, ammonia is shipped to the nitric acid plants to be manufactured into ammonia nitrate. The advantage of ammonia nitrate is that it has a nitrogen content of 35 per cent, in this respect a much more concentrated nitrogen product either for the processes of manufacturing other compounds of nitrogen or for use in the fertilizer industry.

Physical Limitations and Those Fixed by Natural Sources. The competition with natural sources will fix the commercial limitations or selling prices for these various nitrogen compounds, and in considering the possible developments of the processes it will be interesting to see to what extent they have definite theoretical limitations, as these will greatly affect any comparison of possibilities. Before considering in detail these processes we might endeavor to investigate whether our present conception of the physical and chemical reactions involved imposes real limitations, or whether there is an uncertain boundary which further developments may encroach upon, perhaps thus continually improving the efficiency and possibilities commercially. If, for instance, the nitric oxide processes which utilize only 2 per cent to 4 per cent of the energy supplied to the furnace are limited to this amount by the inefficiency of the apparatus, there is much greater possibility of development than would be the case if the process has definite physical or thermodynamic limitations, and the present apparatus utilizes a favorable percentage of this possible ultimate limit. To some extent these theoretical limitations are not always sharply defined, and research will extend this horizon, but we may determine some of these limitations quite definitely.

II. THEORETICAL LIMITATIONS

As we are considering this subject from its engineering aspects, it may be excusable to examine some of the theoretical limitations imposed by the laws of physical chemistry, and in reviewing what may be termed elementary formulas, it is interesting to note that the investigation of these theoretical limitations has been of fundamental importance to physical chemistry in extending the application of the laws of chemical dynamics.

Molecular Inertness of Nitrogen. The elements carbon, C, and nitrogen, N, possess a marked similarity in the fact that the molecule of each is composed of two or more atoms united together with a bond representing a large amount of energy. Nitrogen, having an atomic weight of 14, has a normal molecular weight of 28, indicating two atoms to the molecule, and in this molecular form it occupies 79.2 per cent of the volume of the earth's atmosphere. To separate this molecule into its constituent atoms and cause these atoms to combine with other elements is the problem of the fixation of nitrogen. Unless combined in the atomic form, the enormous bond between the atoms causes them to combine upon themselves into the inert form of molecular or atmospheric nitrogen. The ordinary compounds of nitrogen are formed only by the expenditure of a large amount of energy, the union of molecular nitrogen, N_2, and molecular oxygen, O_2, to form nitric oxide, NO, being represented by the formula

$$N_2 + O_2 = 2\,NO = -43{,}000 \text{ calories}$$

Or in other words, to form one gram-molecule of nitric oxide, NO, requires the expenditure of energy amounting to 21,500 calories.

The general similarity to carbon in this molecular inertness, makes an interesting comparison.

Thus

$$C_2 + O_2 = 2\,CO = 58{,}000 \text{ calories.}$$
$$2\,CO + O_2 = 2\,CO_2 = 134{,}000 \text{ calories.}$$

The formation of one gram-molecule of CO therefore represents the liberation of 29,000 calories, while the formation of one gram-molecule of CO_2 from CO represents 67,000 calories or a total of 96,000 calories in the formation of CO_2 from the original elements C and O. When amorphous carbon therefore is caused to assume the gaseous condition and unite with a molecule of oxygen there are liberated 29,000 calories, but after assuming this condition in which the molecule is no longer composed of the inert carbon molecule, a second gram-molecule of oxygen unites with the CO and liberates 67,000 calories additional. The second molecule of oxygen therefore liberates 38,000 calories more than the first molecule, and as the oxygen molecules were alike, this energy represents the bond uniting the carbon atoms and the energy necessary to break down the bond between these atoms and produce a gaseous condition from the amorphous condition.

Returning to the nitrogen molecule, it is apparent that the formation of the gram-molecule of NO requires 21,500 calories in comparison to carbon liberating 29,000 calories to form CO; that is, the nitric oxide reaction is endothermic while the carbon monoxide reaction is exothermic. Upon adding a second molecule of oxygen to the nitric oxide to form the peroxide we find

$$2\,NO + O_2 = 2\,NO_2 = 27{,}000 \text{ calories}$$

or 13,500 calories per gram-molecule are liberated after previously expending 21,500 calories to form NO. Since there are liberated only 13,500 calories upon adding a second molecule of oxygen, the net energy required to form the NO_2 would be 8000 calories. The first molecule of oxygen required 21,500 calories whereas the second required only 8000 calories, so that 13,500 calories were required by the nitrogen molecule to prepare it for combination with the oxygen.

Dynamic Equilibrium. These heats of combination developed by the atoms combining upon themselves indicate a very stable or inert molecule, and in liberating this energy to assume this more stable form the forces exerted are of large magnitude. It is readily apparent from this, for instance, how carbonaceous gases can readily form soot and cinders and other amorphous forms, when the union with oxygen is disturbed, as the tendency of the atoms to unite with oxygen or to form carbon molecules will depend upon an adjustment of the surrounding conditions. This ever-changing condition of equilibrium constitutes the dynamic conception of equilibrium, displacing the static equilibrium of the older theories of chemistry. In order more carefully to consider some of the theories that have been advanced it may be of interest to follow further some of the concepts of physical chemistry. The fact that the nitrogen atom has this strong tendency to combine upon itself with a liberation of energy greater than in the combination with the oxygen atom, indicates that in any reaction when the combination with oxygen has made possible a changing of the atoms there will be continuously in progress an action and a reaction, and the equilibrium will be indicated by the expression

$$N_2 + O_2 \rightleftarrows 2\,NO$$

the sign of equality being displaced by the two arrows indicating that the action proceeds in each direction, that is, it is a reversible reaction, and the equilibrium will be dependent upon conditions, the two most important conditions being temperature and the active masses of the substances present. Considering first the effect of the active masses present, if it be assumed that the collision of molecules causes the re-arrangement of the atoms comprising the molecule, and that of these collisions only a certain number will cause the re-arrangement to proceed in one direction, the re-arrangement will be greater the more frequently the collisions take place, there being some ratio for each individual case, and the collisions possible will obviously be proportional to the concentration present, that is, the collisions will be proportional to the number of molecules present. With two substances present, the collisions will be proportional to the molecules of each present, and hence to their product.

The Velocity Coefficient. If C_1 and C_2 represent the special concentration of gram-molecules present, the velocity of the reaction will be proportional to C_1C_2 or the velocity V of the reaction will be

$$V = C_1\, C_2 k$$

where k is a constant or coefficient to be determined for the given temperature. This velocity of reaction will proceed each way in reversible reactions; the concentrations of the molecules in the reverse action being represented by C_1' and C_2' and the velocity of reaction by V', the velocity of the reaction in the reverse direction will be

$$V' = C_1'\, C_2' k'$$

where k' is the velocity constant to be determined for the reverse reaction.

The Equilibrium Constant. The chemical driving force for any reaction will continually diminish as the reaction approaches equilibrium, or the velocity of the reaction will diminish as equilibrium is approached, and when equilibrium is reached V will equal V' and

$$kC_1\, C_2 = k'C_1'\, C_2'$$

This dynamic equilibrium indicates that as much reactive substance is being formed in a given time as is being decomposed, and a fixed relation therefore results, but the reactions have not ceased, only the velocities have equalized, and the driving chemical forces are incapable of making any further change in the reacting substances unless the velocity in one direction or the other is changed. In this state of equilibrium the ratio between the velocity coefficients or constants is

$$\frac{k_1}{k} = \frac{C_1'C_2'}{C_1C_2} = K = \text{equilibrium constant.}$$

Or, as the concentration or active mass in any reaction increases, the velocity coefficient increases, and for each change in equilibrium due to temperature change, there is a definite concentration ratio represented by this equilibrium constant K.

Partial Pressures. If the concentration of a given molecule is C and the collisions of the molecule are proportional to this concentration, if there are two molecules the collisions between the two similar molecules will be C times as great as one molecule, or C^2. As the total pressure of a mixture of gases is the sum of the pressure of each gas, and by Avogadro's hypothesis the pressure is proportional to the number of molecules in the given space, the concentrations instead of being represented by gram-molecules C may be expressed as partial pressures p, and equilibrium will be represented by the ratio of the partial pressures of the gases. Thus two molecules of NO will have the pressure p^2_{NO} while p_N and p_O may represent the pressure of N and O At equilibrium the constant K will then become

$$K = \frac{p^2_{NO}}{p_N p_O}$$

and for any pressure and volume the familiar equation

$$PV = RT$$

will represent the work done, where P is the pressure, V the volume, R the gas constant, and T the absolute temperature. The work done in the reaction

$$N_2 + O_2 = 2\,NO$$

will consist in taking one molecule of N from the pressure p and transferring to the pressure P, also one molecule of O from the pressure p to pressure P, and offsetting this work will be the transferring of two molecules of NO from pressure P_{NO} to p_{NO}. When the pressure of a gas at constant volume is increased by the infinitely small amount dp, the corresponding work done dA will be

$$dA = dp\,V$$

The Maximum Work. If we substitute for V its value from the equation

$$pV = RT$$

we have

$$V = \frac{RT}{p}$$

and

$$dA = \frac{RT\,dp}{p}$$

and for the work done between the limits of pressure p and P we have

$$A = RT\int_{P}^{p} \frac{dp}{p} = RTln\,\frac{p}{P}$$

where ln is the natural logarithm. For the work done in forming the NO at a temperature T, we will have

$$N \quad + \quad O \quad - \quad 2\,NO$$

$$A = RTln\,\frac{p_N}{P_N} + RTln\,\frac{p_O}{P_O} - 2\,RTln\,\frac{p_{NO}}{P_{NO}}$$

or, simplifying and assembling the initial pressures and the final pressures in separate terms, we have for constant temperature

$$A = RTln\,\frac{p_N p_O}{p^2_{NO}} + RTln\,\frac{P^2_{NO}}{P_N P_O}$$

But the first term represents the initial pressures or the work done on the initial condition of the materials, and we are not called upon to furnish this energy, the change of energy being represented only by the second term

$$RTln\,\frac{P^2_{NO}}{P_N P_O}$$

This quantity $\frac{P^2_{NO}}{P_N P_O}$ is, however, the ratio of pressures or concentrations represented by the equilibrium constant K, and hence the work done at any given temperature may be represented by the equation

$$A = RTlnK$$

Van't Hoff has applied this type of fundamental equation to a wide range of reactions and by means of the second law of thermodynamics has made it applicable to temperature and concentration changes in which the latent energy plays an important part, for in these reactions the product of the specific heat by the temperature no longer represents the heat transfer.

Van't Hoff's Fundamental Equation. The second law of thermodynamics expresses the relation of A, the maximum work possible at a temperature T, and U, the decrease in energy of the system in relation to the ratio of change of A with the temperature T, the equation being

$$A - U = T\frac{dA}{dT}$$

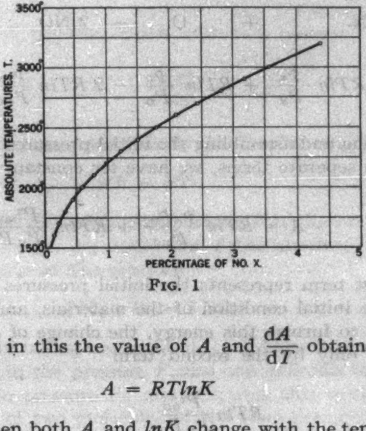

FIG. 1

Substituting in this the value of A and $\frac{dA}{dT}$ obtained from the equation

$$A = RTlnK$$

we have, when both A and lnK change with the temperature T,

$$\frac{dA}{dT} = RLnK + RT\frac{dlnK}{dT}$$

and hence

$$U = - RT^2\frac{dlnK}{dT}$$

which is Van't Hoff's fundamental equation for chemical reactions in which the heats of reaction U are important factors and both the temperature and concentrations may be variable

The quantity U, which in thermodynamics represents the decrease in energy of the system, may here represent the energy of chemical combination, which changes very little with changes of temperature and is generally designated as Q, and in the case of nitric oxide it has the value 21,500 calories per gram-molecule; so the equation becomes

$$43{,}000 = -RT^2\frac{d\ln K}{dT}$$

and when using the air as a source of nitrogen, in which the nitrogen content is 79.2 per cent and the oxygen 20.8 per cent, and letting x represent the percentage of NO formed, as $\frac{1}{2}x$ will be from the nitrogen and $\frac{1}{2}x$ from the oxygen, the equilibrium constant K will be

$$K = \frac{x^2}{\left(79.2-\frac{x}{2}\right)\left(20.8-\frac{x}{2}\right)}$$

Nernst's Determinations of Equilibrium. Nernst and his assistants determined x for a number of temperatures, the calculated and observed values being as follows:

T	X(Obs.)	X(Calc.)	Observer
1811	0.37	0.35	Nernst
1877	0.42	0.43	Jellinek
2023	bt. 0.52 and 0.80	0.64	Jellinek
2033	0.64	0.67	Nernst
2195	0.97	0.98	Nernst
2580	2.05	2.02	Nernst-Finckh
2675	2.23	2.35	Nernst-Finckh

Nernst's calculations of x or equilibrium volumes in per cent of NO, using air at temperatures of 1500 deg. T to 3200 deg. T, are plotted in Fig. 1.

Rapidity of Dissociation. Nernst and Jellinek also determined the rapidity with which the NO is decomposed or dissociated at the various temperatures and these experiments showed that the tendency of NO to revert to molecular N and O is very slight below a temperature of 1500 deg. cent. but increases very rapidly with the temperature, so that the time of withdrawing the products through the varying zones of heat in the electric arc is sufficient to effect a large amount of dissociation. In order to avoid this dissociation a rapid movement of the air through the arc or the arc through the air is desirable, and this in turn causes increased radiation and convection losses, so the maximum possible temperature of the arc is not obtained and hence there are imposed very distinct limitations to the yield of NO.

Haber's Theory of Ionic and Electronic Collisions. Haber and Koenig investigated the possibility of utilizing lower temperatures in the arc to avoid dissociation by enclosing the arc in a water-cooled quartz tube whereby moderate temperatures were preserved. In place of the molecular collisions we have assumed above as due to the thermodynamic condition of the gas, they used a vacuum and endeavored to utilize the kinetic energy from the rapid motion of the ions and electrons liberated by the arc stream under these conditions. Habor considered it possible to increase the thermodynamic concentrations about 50 per cent. His tests indicating that, using a temperature of 3000 deg. cent., it was possible to show 10 per cent concentrations of NO, which would correspond to a temperature under the thermodynamic equilibrium of 4300 deg. cent. Haber gives a table showing the effect of various mixtures of N and O when working with the increased mean free path of the molecules due to a vacuum of 100 mm. of mercury. In his work Haber prefers to use the square root of the equilibrium constant *K* we have used above, thus enabling the partial pressures of the resulting substances to be read direct, while the partial pressures of the ingredients are expressed as square roots of the pressures.

Haber's table for a pressure of 100 mm. is as follows:

Gas mixture				$K = \frac{(NO)}{(N_2)^{\frac{1}{2}}(O_2)^{\frac{1}{2}}}$	Thermodynamically calculated absolute temperature by	
	O_2 per cent	N_2 per cent	per cent NO		Haber	Nernst
Air	20.9	79.1	9.8	0.284	4365	4334
Half-half mixture	48.9	51.1	14.4	0.337	4686	4650
	44.4	55.6	14.3	0.337	4686	4650
Reversed air mixture	75.0	25.0	12.8	0.357	4805	4767
	81.7	18.3	12.1	0.397	5042	5000

The yields of NO per kilowatt-hour obtained by Haber were unsatisfactory and the complications of small water-cooled tubes and working under a vacuum of 100 mm. have not justified commercially the higher concentrations of NO he obtained.

Commercial Processes now in Use have Distinct Limitations. We may assume that up to the present the processes in commercial use are limited strictly by the thermodynamic equilibrium of the Van't Hoff equation. As the volume of gases when working with low concentrations of NO is considerable, the radiation and convection losses as well as the transfer of sensible and latent heat from the arc to the gases lower very materially the temperature of the arcs, and the yields therefore indicate an average working temperature of 2200 deg. cent. to 2500 deg. cent., or concentrations of 1.5 per cent to 2 per cent NO when working with air. These theoretical limitations of the direct process of forming NO have therefore led to many efforts to dissociate the nitrogen molecule by other means.

Sources of Chemical Energy. Naturally the sources of chemical energy have offered a most fruitful field, but, like the synthesis of carbon compounds, a considerable elevation of temperature is necessary before the chemical energy becomes effective enough to break the bond of the nitrogen molecule. At these elevated temperatures practically all elements or compounds which release sufficient energy to combine with nitrogen have a greater combining power for oxygen, so the processes cannot be conducted with air but involve the separation of the nitrogen from the oxygen of the air as a preliminary step. The compounds of nitrogen thus formed do not, therefore, include the oxides of nitrogen. The common elements exhibiting the most pronounced tendency to combine with nitrogen are calcium (Ca), magnesium (Mg), aluminum (Al), boron (B), etc. The carbides of a large number of metals also exhibit a pronounced tendency to combine with molecular nitrogen when heated.

The great advantage from a theoretical standpoint in utilizing these processes is that the reaction with nitrogen may be made more complete, as equilibrium may be continually disturbed by withdrawing the compound of nitrogen formed or by presenting to the nitrogen to be combined fresh combining surfaces of the substance and the action may be caused to proceed practically quantitatively, thus avoiding heating large quantities of materials which are inert to the reaction. A vast field of research is opened by these possibilities, as very few of the equilibrium figures have been determined, and it is almost certain that direct combustion methods may eventually be evolved along these lines.

The experimental data are so meager that no theoretical limitations can be placed. The reactions assume unusual importance, however, on account of a wide application in the arts. This may be best illustrated by considering the formation of calcium carbide, CaC_2, in relation to its three reversible reactions, namely

$$(1)\quad CaO + 3C \leftrightarrows CaC_2 + CO$$

$$(2)\quad CaC \rightleftarrows Ca + C$$

$$(3)\quad CaO + C \rightleftarrows Ca + CO$$

There are here six substances, some in solid form, some in liquid and some gaseous (molecular and atomic) and it is evident that the temperature will have a marked influence on the equilibrium which will exist, and the reaction will be greatly affected by very minute changes, for the partial pressure of the gases will be suddenly changed by such conditions as the carbon released in a gaseous state immediately combining to form amorphous carbon, or the metallic calcium vapor combining with the oxygen released by the CO to form calcium oxide which immediately precipitates as a solid. The fact that calcium oxide, which is most refractory, can be vaporized at a temperature of 1600 deg. cent. to 1800 deg. cent. in the sense that the calcium is vaporized and decomposes CO to precipitate CaO again, is one of the actions similar to the fumes in smelting furnaces which accounts for a heavy loss of metal at temperatures not ordinarily capable of producing fusion. When nitrogen is inserted in a reaction of this kind, there are immediately formed complex carbon-nitrogen compounds, but the action of the oxygen present is to dissociate these, allowing the nitrogen to combine into the molecular form and the metal to precipitate from the fume as a minute particle of metallic oxide, the carbon precipitating as amorphous carbon in the form of soot, as all of these reactions liberate a large amount of energy. The temperature of these reactions is from 1500 deg. cent. to 2000 deg. cent. and is therefore well within the range of combustion methods if the combustion could be in contact with the substances as in the blast furnace, but the presence of the oxygen necessary for combustion prevents the formation of nitrogen compounds.

The effect of partial pressures in these reactions is of fundamental importance. The active mass of a solid is constant and hence at the boundary surface where the solid and gases meet there is a high velocity of reaction. Equilibrium will be produced either by the solid forming a coating of the compound which will place it in equilibrium or by the pressure of the gases generated from the reaction producing a condition of equilibrium. Taking the familiar calcium carbonate reaction as an illustration,

$$CaCo_3 \rightleftarrows CaO + CO_2$$

There being two substances in the solid state and one in the gaseous, the equilibrium constant *K* will be

$$K = \frac{CaO \times CO_2}{CaCO_3}$$

where CaO and $CaCO_3$ are the very slight vapor pressures of the solids, that is, the sublimation pressures, which in practise are too small to measure. The pressure of the CO_2 will be practically the total pressure, and as this varies, the velocity constant *K* will vary and hence for any temperature there is but one pressure for equilibrium. LeChatelier measured the temperatures and pressures of the above reaction over a wide range and found a variation in the temperature necessary to produce the reaction of from 547 deg. cent. at 27 mm. pressure, to 865 deg. at 1333 mm., or in other words, equilibrium could be produced through a range in temperature of 60 per cent, and at one point a change of two degrees necessitated a change in pressure of over 10 per cent in order to restore equilibrium. Rothmund found the equilibrium pressure of CO in the carbide of calcium reaction to be 250 mm. at 1620 deg. cent. If the CO pressure was raised above the equilibrium figure at this temperature CO was absorbed and no carbide was formed. By inserting inert gases so the CO was diluted and its partial pressure reduced, the temperature of the formation of carbide was varied over 20 per cent. These results all indicate that for the nitrogen reactions, the actions and reactions must not only be subject to accurate temperature regulation but the partial pressures must be controlled and it is probable that definite zones of reaction must be maintained. The present commercial applications such as the Serpek and cyanamide process prepare the compounds of nitrogen by causing the nitrogen to react largely with the solid masses and thus avoid many of these complications due to the vapor processes, or variable minute pressures of sublimation.

By substituting the resistance furnace for the arc and reducing the metals in the presence of nitrogen, thus forming nitrides, or forming carbides and treating these in the presence of nitrogen, there have been developed a number of processes which have been commercially applied.

III—DESCRIPTION OF PROCESSES

Three processes which have been commercially applied for directly preparing nitric acid from atmospheric nitrogen are, first, the Birkeland-Eyde;se cond, the Schonherr; and third, the Pauling. These are diagrammatically shown in Figs. 2, 3, and 4. Fundamentally, all operate on the same principle of forcing air into intimate contact with a high-tension arc and withdrawing the product, nitric oxide, NO, as directly and rapidly as possible in order to reduce the amount of decomposition of the resulting product. As these processes have been repeatedly described in detail in the technical press, we will confine our attention to general comparisons.

Birkeland-Eyde Process. The Birkeland-Eyde furnace, illustrated in Fig. 2, has been the most extensively used. Its most distinctive feature is the use of the magnets *A* which distort the arc into a series of great wheels of flame, extending radially outward from the electrodes *E*, located normal to the paper in Fig. 2. The air enters through the conduit *C* and is distributed to the arc through the holes in the firebrick lining. The products are withdrawn from around the periphery at *D*. The voltage of 10,000 volts is reduced by an inductive reactance coil to about 5500 volts across the electrodes. The alternating current of 50 cycles establishes the arc across the *U*-shaped water-cooled electrodes *E*, spaced about 0.3 in. (8 mm.) apart and a flow of current takes place across this ionized path, the electrons formed being repelled by the intense magnetic field of the direct-current magnets, *A*, and their discharge radially outward causes the arc stream to follow until it is deflected outward in a great semicircle. As its length is thus increased the potential across the electrodes rises and a second arc is established, the effect being to make a series of rapidly expanding arcs which are expanded across the entering air spaces. As the arcs travel radially outward the contact of the ionized arc stream with the incoming air disrupts the nitrogen molecule and causes the formation of NO, and the gaseous products travel rapidly to the periphery of the furnace, where they are withdrawn at an average temperature of about 1250 deg. cent. The earlier Eyde furnaces were of 300 kw. capacity and gave a concentration of about 1.5 per cent NO and a yield of about 500 kg. of nitric acid per kw. per year. The more recent furnaces are of 3000 kw. capacity and give concentrations of about two per cent NO and a yield of 580 to 600 kg. of nitric acid per kw. per year, or 65 to 70 grams of nitric acid per kw-hr.

Schonherr Process. The Schonherr furnace (Fig. 3) consists of a long iron pipe 4 having an electrode *E* inserted in the bottom and the tube itself is the other electrode, the distinctive feature of the process being that an alternating current at 4500 to 5000 volts maintains an arc of from 23 to 25 feet (7 m. to 8 m.). The furnace is started by forming an arc from the lower electrode to the wall of the iron pipe by means of a lever *Z*, a blast of air is then admitted to the pipe, whereupon the ionized gases are caused to ascend and carry with them the arc stream. In this way the arc is caused to travel toward the upper end of the

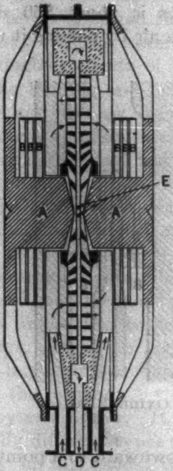

FIG. 2—BERKELAND-EYDE FURNACE
A, core; B, windings; C, gas entrance; D, exit.

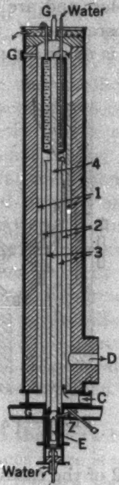

FIG. 3—SCHONHERR FURNACE

tube, where it is maintained. In practise, the air stream is admitted in a tangential direction, causing a whirling motion to be imparted to the air surrounding the arc; this creates a vortex motion causing the arc to be surrounded by the cooler air and thus protects the iron pipe, which is wholly unlined. The rapid passage of the air maintains an ionized path for the arc stream and the arc burns quietly. The products are withdrawn from the upper end and pass downward through the passes, 1, to the outlet *D*. Previous to being withdrawn they are cooled by the water cooler and are further used to preheat the entering air. The temperature of the exit gases is about 850 deg. cent. Provision is made for preheating the air by passing it upward in the space 2 of the casing and then downward to a point opposite the electrode. The largest furnaces are of 800 kw. capacity and maintain an arc about 23 ft. (7m.) long. They give an NO concentration of about 2.25 per cent and a yield of 550 to 575 kg. per kw-year or 65 grams per kw-hr.

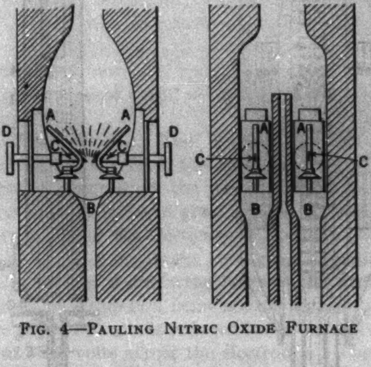

FIG. 4—PAULING NITRIC OXIDE FURNACE

Pauling Process. The Pauling furnace (Fig. 4) establishes an a-c. arc of 4000 volts between two curved horns much after the pattern of the horn type lightning arrester. This arc when established is driven upward by a blast of air admitted at *B* and is disrupted by the diverging horns. A sheet of arc flame is maintained by re-establishing a new arc as the previous one is elongated. The effect is to create an arc flame about 30 in. (75 cm.) high and to have this flame in intimate contact with the rapidly moving air used to blast the arc flame. Two furnaces are usually operated together and to assist in a rapid cooling of the products a portion of the previously heated or partially cooled discharged gases is admitted to the top of the furnace. The arc is established by the high voltage breaking down the gap between narrow blades *C* located in the horn gaps, and as these wear away they are continually advanced by the adjustments *D*. The percentage of NO obtained is 1.25 to 1.5 per cent in the 400-kw. furnace, while the yields are 525 to 540 kg. per kw-year or 60 grams per kw-hr.

Power Factor and Electrode Wear. In all these processes where the arc is distorted the power factor is about 70 per cent, being about 5 per cent lower in the Schonherr type, apparently due to inductive effects of the iron pipe surrounding the arc. In both the Pauling and Schonherr furnaces the electrodes are adjustable and the air blast plays directly on the electrodes, necessitating this adjustment and also means of easy renewals. The Pauling blades last less than 24 hours; the Schonherr electrode is a straight rod of iron and is fed upward as it burns away. The Eyde water-cooled copper pipe, not being directly in the path of the air blast, lasts three to four weeks. In the operation of both the Eyde and Schonherr furnaces a furnace is placed on each separate leg of the three-phase circuit so that six wires are used for each generator. In the installations that have been made the furnaces are connected direct without transformers, and as no parallel operation of generators is attempted a large number of cables is required between the power house and the furnaces.

Efficiency and Losses. It will be noted that notwithstanding the radically different types of these furnaces there is not a wide divergency in the yields, the Schonherr furnace showing the highest concentration of NO, while the Eyde probably produces a slightly higher output per kw-hr. All of these concentrations indicate that the maximum temperature of the arc is not utilized but is very considerably reduced by the large amount of air admitted. If the temperature of the arc is raised by admitting less air there is a heavier decomposition of the products and all products are heated to a higher temperature with a corresponding loss, the net result being a lower yield per kw-hr. As the yield per kw-hr. is of fundamental importance, adjustments are governed accordingly. The concentration of NO affects directly the apparatus for recovering the products, such as the absorbing towers, and the lower the concentration of NO the greater the losses from heating the inert gases. The furnace efficiency will largely be determined by this factor. Let us take for example a concentration of 1.75 to 2 per cent NO and examine the distribution of heat. If we take the specific heats of a molecule of the diatomic gases as constant, there will be no difference in the specific heats per molecule of N, O or NO, and taking a standard value for this, we may calculate the heat energy expended. Let us assume, following Haber, that for a change of temperature t, the specific heat per molecule will be

$$6.8 + 0.0006\,t$$

The gaseous products heated in the furnace with 1.75 to 2 per cent NO concentrations will have, from Nernst constants, an absolute temperature of about 2500 deg. and the air would have an initial temperature say of 27 deg. cent. or 300 deg. absolute, so the arc would raise the temperature of the 100 molecules through 2200 deg., or,

$$\text{sensible heat} = 100\,(6.8 + 0.0006\,t \times 2200\text{deg.})\ 2200\text{ deg.} = 1{,}786{,}400\text{ calories.}$$

As two molecules of NO require a latent heat of formation of 43,000 calories, the total heat will be 1,829,400 gram-calories; and as one watt-hour equals 860 gram-calories the energy represented will be equal to 2.12 kw-hr. for two gram-molecules of NO. Taking the atomic weight of N as 14 and of O as 16, the gram-molecule of NO will weigh 30 grams, so 2.12 kw-hr. will form 60 grams of NO.

If we mix this NO with air and water it will form nitric acid without requiring a further expenditure of energy, thus,

$$2\,NO + 1\tfrac{1}{2}\,O + H_2O = 2HNO_3$$

and the 60 grams of NO will then become 126 grams of HNO_3; the production of nitric acid will then be 126 grams per 2.12 kw-hr. or 59.4 grams of HNO_3 per kw-hr. Of this expenditure of 2.12 kw-hr. the formation of the nitric oxide utilized

$$\frac{43{,}000}{1{,}829{,}400} = 2.35\text{ per cent,}$$

and the sensible heat imparted to the active gases to raise their temperature to form two molecules of NO required 35,728 calories, so this represented

$$\frac{35{,}728}{1{,}829{,}400} = 1.95 \text{ per cent,}$$

while the heating of inert nitrogen and oxygen, or that portion of the air which was not utilized but which was heated to the furnace temperature, was represented by

$$\frac{1{,}750{,}672}{1{,}829{,}400} = 95.7 \text{ per cent.}$$

These calculations, while open to some criticism on account of the uncertainty of the figures for specific heat and its change with temperature, closely approximate the conditions, and indicate that low concentrations of NO when formed from thermal reactions are extremely wasteful. If concentrations of 10 per cent NO are obtained with temperatures of 4200 deg. to 4300 deg. cent. the yields may be increased to 135 to 140 grams of HNO_3 per kw-hr., but the greatest saving in energy will result in utilizing other than purely thermal energy. While thermal energy may be produced more cheaply directly from fuel, its temperature possibilities are again limited by the inert gases of combustion if air is the source of these.

Hausser has commercially applied a process for utilizing coke oven gases by means of an explosion bomb. The amounts of excess gases may be limited and the intimate mixture of combustible and oxygen due to pre-compression of the charge permits of high combustion temperatures being reached. Fig. 5 shows this bomb having a capacity of 1600 cu. cm. The gases, either illuminating or coke oven gases, enter through the inlet after previously exhausting the air by means of the air pump outlet. Means are provided at *a* for injecting under high pressure a spray of water to cool the products as quickly as possible. The ignition takes place at *Z* by means of a high-tension spark and the explosion is propagated outward from this point and the vapor condenses on the enamel lining of the bomb.

With this device Hausser obtained a temperature of 2100 T and concentrations of NO of 0.5 per cent. The temperature calculated from the assumed figures for specific heat indicated a concentration of 0.3 per cent for equilibrium by the Nernst calculation and Hausser sought to explain this increase of yield as due to a chemical reaction induced by photo-chemical effects similar to the ionization by ultra-violet or actinic rays of light. The maximum yields were 99 grams of HNO_3 per cu. m. of gas, or equivalent to 6.2 lb. of HNO_3 per 1000 ft. of gas. A commercial plant on this system has been installed in Germany. This low concentration of NO greatly complicates the commercial application, as the absorbing devices are more cumbersome and the percentages of loss are higher.

Method of Utilizing NO. All of the above nitric acid processes utilize the reaction

$$2\,NO + O_2 \rightleftarrows 2NO_2$$

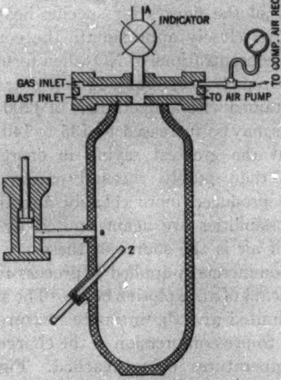

FIG. 5—HAUSSER PROCESS

which is an exothermic one for the formation of the peroxide, and if the temperatures are controlled, side reactions can be prevented and equilibrium can be maintained with only a small percentage of NO remaining. The gases after leaving the furnaces are usually carried through waste heat boilers where 50 to 60 per cent of the heat is utilized for steam production. They are then cooled in aluminum pipe coolers and allowed to enter a gas holder where time is given to form the peroxide. The products then enter counter-current absorption towers where the reaction with water forms

$$2NO_2 + H_2O = HNO_3 + HNO_2$$

The nitrous acid HNO_2 is further oxidized and utilized to form HNO_3 in contact with the excess oxygen in the gases and with the absorbing water. The final recovery is usually made by circulating the gases through two towers of weak alkaline solution, such as sodium carbonate, and this is converted into sodium nitrate and into sodium nitrite, and recovered by evaporation; the final products are a combined nitrate-nitrite of sodium. A normal circulation over three absorbing towers gives an acid of about 30 per cent concentration but this can be increased to 45 or 50 per cent by recirculating over the first tower. Further concentrations are usually made by evaporation. All of these processes are simplified by increased concentrations of NO in the initial reaction. About two to three per cent of the original NO is discharged in the waste gases from the absorbing towers. It will be noted that one great advantage of these processes is that they require the handling of only air, gas and water up to the time the nitric acid is formed in the absorbing towers, so that the simplest handling devices suffice, and the labor is a minimum; also no chemicals are required until the final washing with the alkaline solution in the absorbing towers, and this may be a cheap solution such as lime water if conditions make it desirable.

Cyanamide Process. The very low yields, representing less than 5 per cent of the energy expended and amounting to 65 kw-hr. per kg. of N fixed, naturally have turned attention to chemical reactions as a means of increasing the yields. One of the most important of these is the process for making cyanamide, $CaCN_2$. As a separate paper is to be presented here covering this subject, we will only generalize.

The endothermic reaction and the heating of the materials entering into the calcium carbide reaction have an approximate theoretical value of 3.1 kw-hr. per kg. produced, whereas it requires about 4 kw-hr. to produce a kg. of 85 per cent calcium carbide in the best practise. For 100 per cent carbide it would require 4.7 kw-hr. and the efficiency, is therefore,

$$\frac{3.1}{4.7} = 66 \text{ per cent.}$$

The union of carbide and nitrogen is exothermic when a sufficient temperature is reached, so the actual expenditure of energy for this reaction is not in excess of 0.1 to 0.2 kw-hr. additional for the fixation of the nitrogen. We require further the preparation of the nitrogen, and the grinding of the carbide to prepare it for the nitrogen treatment. The cyanamide can be used directly in the fertilizer industry, but for use in the chemical industries it must be decomposed to form ammonia, or if nitric acid is required it must be made from the ammonia by some process such as the Ostwald contact process. We may figure, however, that the yield for a given amount of electric energy, which amounts to about 16.6 kw-hr. per kg. of N fixed, is from four to five times the yield of the direct nitric acid processes, while offsetting this is the cost of preparing the nitrogen, the cost of chemicals, the handling of materials at high temperature, and the many factors making up manufacturing costs.

The Serpek Process. The Serpek process is typical and has been quite extensively introduced commercially. The reaction is represented by the equation

$$Al_2O_3 + 3C + N_2 = 2AlN + 3CO$$

The reacting temperature for best results is claimed to be 1800 deg. to 1900 deg. cent., but no effort is made to define the equilibrium conditions and it is very evident that where CO enters so actively into the reaction the temperatures can be materially altered by a change in the partial pressures of the N and CO. One of the most interesting features of this process is that the impure Al_2O_3 in the form of bauxite is fed into the furnace together with coal and the sensible heat is therefore partially derived from the coal. Neglecting the specific heats of the solids, the endothermic reaction requires three kw-hr. per kg. of aluminum nitride, having an approximate content of 26 to 34 per cent N; it would require therefore 9 to 10 kw-hr. per kg. of N under the best conditions if the coal and producer gas were capable of supplying all the heat energy needed to produce the required temperature in the gaseous and solid products. In the case of cyanamide it requires about 4 kg. of high-grade carbide per kg. of nitrogen, or a kg. of N requires 16 kw-hr. under favorable conditions and about 0.2 kw-hr. for heating the carbide, against 10 to 12 kw-hr. in the Serpek process. If all energy were supplied from the electric source the Serpek process would require practically the same electrical energy as the cyanamide process.

There is a distinct advantage in being able to use producer gas in place of preparing purified nitrogen and there is a further advantage in conducting the process with one operation. In practise Serpek uses a revolving barrel furnace of the resistance type, the resistance consisting of a squirrel-cage construction which continually agitates the material as it passes through. In all nitride reactions this is essential, as the materials become coated with a covering which protects the interior and prevents further absorption of nitrogen. Serpek feeds bauxite and coal from a producer type of furnace into this revolving electric furnace and the sensible heat is thus utilized to heat the material as it travels to the electric furnace The product is discharged from the electric furnace as aluminum nitride with a content of 26 per cent to 34 per cent N.

The aluminum nitride can be treated with steam and the N converted into ammonia or the ammonia may be converted into nitric acid. Serpek claims a process for converting the nitride directly into nitric acid, but no details are available. One drawback to using bauxite is that the resulting aluminum oxide is more difficult to use than the impure bauxite and the process does not work as economically. It is probable that some cheap catalytic agents may be found to substitute for the bauxite, but otherwise the Serpek process should necessarily find its greatest application in connection with the reduction of aluminum.

Haber Catalytic Process. One other process which has attracted marked attention on account of the scientific eminence of its inventor as well as the commercial results obtained is the Haber process for the synthesis of ammonia directly from its components N and H. This means that there must be a supply of these elements available or they must be cheaply produced. The reaction is an exothermic one producing 11,000 calories per gram-molecule so the problem is not so much the energy consumption as the peculiarities of the reaction

$$N_2 + 3H_2 = 2NH_3$$

The ammonia formed is practically decomposed at 750 deg. cent. It has been difficult to get any substance to react with the N at this low temperature, and while the nitrogen was made active toward many substances it was easy to decompose the resulting NH_3 into its constituent molecules and all yields obtained were too low to justify commercial results. Haber's success seems due more to ingenuity in constructing his apparatus and to the discovery of a suitable catalyzer than to any departure from previously known principles. The fact that one molecule of N and three of H form only two molecules of ammonia indicates that the volume occupied by the ammonia will occupy only one-half the space occupied by its constituent gases and hence this contraction of volume will be assisted by pressure. Haber increased the pressure on the reacting gases to 200 atmospheres, and as a catalyzer he used uranium. He found at 500 deg. cent. he could react on the nitrogen and upwards of 8 per cent of ammonia could be formed before equilibrium took place. By using limited amounts of N and an excess of H the equilibrium pressures were adjusted well within the decomposition limits of temperatures and by withdrawing the gases from the catalyzer as they reached equilibrium the process was made continuous. The fact that decomposing ammonia creates a most destructive corrosive agent had to be met and the retorts had to be made strong enough to stand the effects of the high pressure, and also possible explosions, as hydrogen compressed to 200 atmospheres and heated to 500 deg. cent. is a most active agent in the presence of impurities such as oxygen, sulphur, etc. The retorts can be made of very moderate size, and a number of them used, and by heating internally with electric resistance the shells are not subject to the effects of temperature, so the process seems to have met with very pronounced technical success. The consumption of energy for heating the gases is very slight as the exothermic reaction will compensate largely for the heat required to release this.

The preparation of the N and H and the compression to 200 atmospheres will represent the greatest costs of production. It will be noted that all products are handled in the gaseous condition, being most favorable for low labor costs. The ammonia is extracted from the mixture of N and H by slightly cooling the gases until the point of liquefaction of ammonia is reached and the ammonia condenses out. The remaining gases are passed back to the retort without sacrificing the original pressure of compression. The work done on the gases is thus reduced to a minimum and equilibrium can be continually disturbed by withdrawing the products without heavy losses This process involves the expenditure of approximately 1.5 kw-hr. per kg. of N and therefore represents the lowest consumption of energy of any of the fixation processes.

From an engineering point of view the various processes must be considered from other than the technical standpoint, the question of particular application being the guiding consideration in most cases.

IV—THE ECONOMICS OF NITROGEN FIXATION

Fertilizers. In considering nitrogen fixation and its relation to fertilizers we must remember it is only one of the three important ingredients of fertilizers, the other two being phosphorus and potassium. It is possible to obtain nitrogen from the atmosphere and transfer it to the soil by means of nitrifying bacteria which may be cultivated by such plant life as the legumes, to which family belong the clover and alfalfa. These plants have a nodule on the stem which is the seat of the bacterial activity and if the plants containing this nitrogen are returned to the soil the soil may be enriched in nitrogen, but the crop must be sacrificed or partially so. When it is not desirable to plant these nitrifying crops recourse must be had to nitrogen in the form of fertilizer. Unfortunately all crops deprive the soil of fertility, and in the case of phosphorus and potassium converted into the crops, these must actually be replaced, or barren soil will eventually result. Each soil must be treated for the particular crop it is to bear and usually there are fixed mixtures which become standard for various crops. These mixtures contain the nitrogen, the phosphorus and the potassium in varying amounts. The output of nitrogen from a chemical works would ordinarily be shipped to these fertilizer manufacturers unless the chemical works desired to manufacture the mixed fertilizers.

Of all the processes we have considered, the cyanamide is the only one which manufactures a product which is in a form to go into the fertilizer market direct. The nitric acid processes must unite the acid with some alkaline base such as sodium, lime or ammonia and the ammonia processes must unite the product with an acid such as sulphuric or nitric. The nitride processes can hardly afford to ship the nitride, as it is combined with an ore or base such as aluminum oxide which may be more desirable in the aluminum industry, as the fertilizer industry will pay only on a nitrogen basis.

Prices of Nitrogen. In general the price of combined nitrogen, as we have seen, is fixed by the price of Chile nitrate. Thus if this sells for two cents per lb. and contains 15 per cent N the price per lb. of N is 13.2 cents and this in turn would make the price of ammonia sulphate having 21 per cent of nitrogen 2.7 cents per lb. These have been current prices. In considering the production of nitrogen products, it would seem that while these prices control nitrogen for the fertilizer industry, it would be desirable to produce if possible products which are manufactured from these crude products, and thus avoid direct competition with the natural products. Nitric acid of commerce is manufactured from soda nitrate by treatment with sulphuric acid, about 72 per cent of the sodium nitrate being nitric acid. As the by-products of this operation only partially pay the costs, the manufacturing costs leave the nitric acid with a value of 50 per cent over the value as nitrate. Hence a chemical works could afford to produce nitric acid when it could not afford to add a manufacturing cost to produce a fertilizer from the nitric acid and then sell it in competition with the crude Chile nitrate.

A large portion of the phosphate rock of this country is treated with sulphuric acid to form the so-called superphosphates. If nitric acid is used in place of sulphuric acid the superphosphate can be produced at the same time as a fertilizer of lime nitrate, or if preferred a high concentration of phosphoric acid can be produced from lower grade phosphate rock. Industries of this kind promise more favorable results commercially than does the direct production of fertilizer. If low grade-products are manufactured at close prices a very large volume of business is a necessity, and works of this character and magnitude are more apt to be a result of successful development rather than an initial venture in a field beset with uncertainties as to the profits and the chances of a development of other processes reducing these if they are problematical.

Costs of Making Products. Let us consider more in detail some of the costs. We may assume approximately that the labor and repairs in furnace room and absorbing tower will cost $10 per ton of nitric acid and if nitric acid is selling for $60 per ton, we have a margin for power cost, interest, general expense, etc., of $50, and if we produce 500 kg. of acid per kilowatt-year it will require two kw-yr. per metric ton or $25 per kilowatt-year, and we must absorb all interest charges and general expense in this. If the yield can be made 550 kg. per kilowatt-year and we can sell for $60 per short ton, we will require 1.8 kw-yr. or $28 per kw-yr. We must assume that the product does not have to be packed for shipment and that there are no selling costs involved, and we must figure on an output so that our units may be large enough to bring the investment in plant down to $80 per ton of acid so the annual charge may be $8 or net $20 per kilowatt-year, and if $5 are allowed for general expense the best we can do will be about $15.00 per kilowatt-year.

We see it would be hopeless to attempt to put this acid into a product to compete with the fertilizer prices, for they are some 50 per cent lower in selling price, and it will involve a cost for some raw material to mix with the acid, the cost of manufacture and a packing and shipping charge. We must then abandon any idea of making fertilizer from nitric acid prepared by the direct oxidation of atmospheric nitrogen in the electric arc until such time as we can improve the very low efficiency due to the thermodynamic limitations of the reaction. We can only hope to utilize this process in the manufacture of nitric acid coupled with some other product which will procure for it a higher price. There is, for example, a limited demand for the nitrite of sodium $NaNO_2$ used in the dye industry, and this is manufactured by reducing nitric acid with molten lead, thereby adding another manufacturing operation to the acid cost. This nitrite may be cheaply made by taking a mixture of NO and NO_2 such as we would have in parts of the system and passing it into water or sodium hydroxide, thus

$$NO_2 + NO + H_2O = 2\,HNO_2$$

or,

$$4NO + 2\,NaOH = N_2O + 2\,NaNO_2 + H_2O$$

and this process would produce a product selling for four to five cents per lb. We must remember, however, that the price of nitric acid is not a fixture and that a cheap combined nitrogen fertilizer will cut the price of sodium nitrate and hence the price of nitric acid. We are confronted, then, with the fact that all processes will be affected by the success of any one process that is a large enough success to affect the market conditions of combined nitrogen and upset the ruling prices in the fertilizer industry. It is useless to look only to cheap power as a solution of this problem, as the real solution is in the improvement of processes.

Let us roughly compare the power requirements of the processes as we have outlined them above and we find

Direct oxidizing of atmospheric nitrogen 5 per cent efficiency, yield at 550 kg. per kw-year, requires per kg. of N.	65 kw-hr.
Cyanamide process 66 per cent efficiency in carbide 1 per cent loss in heating to combine with N, requires per kg. of N,. . . . . Also preparation of N.	16.6 "

Aluminum nitride using coal to heat products to temperature of reaction requires per kg. of N.......	12	kw-hr.
Catalytic method of combining N and H to form ammonia, requires per kg of N...............	1.5	"
Also preparation N and H, refrigeration, and compression to 200 atmospheres.		

The general tendency abroad in figuring the cost of water power is to give only the operating costs, and from this one sees costs of producing power figured at from 50 cents to $1.00 per kilowatt-year, and in using these figures erroneous ideas have been widely circulated. In this country it has been standard practise to consider the investment in the power plant, that is, the cost of the development and the property, as fixing very largely the cost of producing the power. It is quite common to have labor and supplies cost not more than one dollar per kilowatt-year, but this would not be considered as representing the cost of the power. Where a chemical industry owns the hydroelectric power plant as well as the chemical works, the foreign practise is inclined to consider the investment as a whole and apportion the costs of operation to the various departments, while interest on the capital is charged to the profits. The costs of producing power are therefore uniformly much lower than we are accustomed to figure on. There are many plants in operation in the chemical industries abroad whose real costs of producing power are no lower than many of the more favored locations in this country.

Off-Peak Loads. One of the chief interests in the chemical utilization of electrical energy is centered in the possibilities of off-peak or off-season loads, as American plants generally have a certain proportion of power which can be disposed of to better advantage than selling the entire output as low-priced power to chemical industries. This off-peak power is difficult to utilize in furnace work, where the cooling of the furnace and its charge is an important factor both from the standpoint of cost and of output, and again, adjustments may be so disturbed from an interrupted output as to be absolutely impracticable. One of the possible solutions for off-peak utilization appears to be in the adoption of some system where fuel is also utilized and the radiation losses are not excessive under conditions of banked fire when the electric portion of the heat energy is not in use. Some of these combination processes may promise a solution of the off-peak load situation more attractive than the straight electric furnace, which is difficult to cool down entirely without unduly affecting the conditions. In all plants the volume of output is the determining factor in absorbing the general overhead charges, and any intermittence must diminish output, with its accompanying disadvantages.

If the furnace could be operated on the off-season load and its product stored, and the chemical works utilizing this product could operate on a normal schedule, this would form one solution; or another would be if by chance the off-season power were available at the time the greatest demands were to be met, such as preparing a fertilizer product at the season of fall rains for the early spring delivery. All of these plans, however, suggest the necessity of operating at least a portion of the plant continuously in order to meet fixed charges and preserve an operating organization. If the chemical works requires a moderate amount of power for its processes in year-round operation and only its surplus for manufacturing its crude material at the off season peak it promises the greatest possibilities.

The future of nitrogen fixation is alluring and promises many developments along lines other than those we have considered, but already the market has felt the effects of these various processes, and instead of nitrogen being figured at thirteen cents per pound, it is confidently predicted it will very shortly find its level at a selling price of about eight cents, making a cost of production of five to six cents per pound and thus reducing sodium nitrate to about 1.33 cents per pound, or approximately $30 per long ton, and the lower grade mines will feel this and be forced to curtail.

It therefore seems very certain that before 25 years shall have elapsed since Sir Wm. Crookes made his memorable address, the Chile nitrate beds will have vastly curtailed their production, not from exhaustion but from the inroads made by the onward advance of chemical and electrochemical engineering.

DISCUSSION ON "FIXATION OF ATMOSPHERIC NITROGEN," (SUMMERS), NEW YORK, MARCH 12, 1915.

Joseph W. Richards: In considering the arc process, we can say that it is essentially an electrochemical process. Last summer I had the pleasure of visiting the largest of these plants in operation at Rjukanfos, in Norway. In a valley that five years ago contained five houses, there is now a town of ten thousand inhabitants, with a power plant of 250,000 h.p., and they are shipping their products practically all over the world.

The cyanamide process had also its origin in an electrochemical establishment. Mr. Wilson, down in the South, tried to make aluminum in an electric furnace. He put some lime in the furnace, accidentally making calcium carbide. That was the root of the cyanamide process, so that it is essentially electrochemical in its origin.

The Serpek process originated in the discovery that metallic aluminum could absorb nitrogen from the air, and that the product when acted upon by water gave off ammonia, giving rise in the mind of Mr. Serpek to a commercial method for manufacturing aluminum nitride, and decomposing it to get ammonia.

The thing that makes these processes most interesting is their wonderful inefficiency from the thermal and energy standpoint. Regarding the 250,000 h.p. used in Rjukanfos, Norway, there is actually utilized for the chemical operation 3500 h.p. All the rest of the 250,000 h.p. is lost, the efficiency of that operation being about 1.4 per cent on the power used. We were used to such inefficient operations in the past, in such cases, for example, as melting crucible steel, which had a fuel efficiency of 2 per cent; but in so many cases have we progressed that the wonderful room for improvement here is one of the most striking, one of the most interesting and most attractive things about the whole subject to the electrochemical engineer.

The cyanamide process, however, does considerably better as far as power consumption is concerned, and it rises to over 6 per cent, as I calculate the thermal efficiency. From Mr. Washburn's remarks,* the very favorable comparison of the cyanamide process to the arc process probably has its deepest root in the higher thermal efficiency. The Serpek process, if it could be worked, would be approximately of the same thermal efficiency as the cyanamide process, but up to the present time it has not been commercially operative, although perhaps a half million dollars have been spent upon experimental work. One cannot help feeling, however, that something may result from that expenditure and that by some modifications of their fundamental ideas, as to how to conduct the process, the process may become commercially successful.

The Serpek process produces alumina as a by-product. If it produced all the alumina required in the aluminum industry, there would be only 40,000 tons of nitrogen produced yearly as a maximum.

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*"The Cyanamid Process", by Frank B. Washburn. Presented at joint session with Am. Electrochem. Soc.

Theoretically the union of nitrogen with oxygen at 100 per cent efficiency should give about one kilogram of nitrogen per h.p-hr., or approximately 1320 g. of nitrogen per kw-hr. The cyanamide process gives about 70, and the arc process about 16, so that the great room for improvement is at once evident.

The possibility of converting the ammonia produced from cyanamide into nitric acid by a highly efficient process is undoubtedly an important question. I have seen one such process in operation at between 90 and 95 per cent efficiency on the ammonia produced. All these small details of the operation of the process fade, I think, when considering the thermal inefficiency and the great room for improvement which is still possible. It is such a rapidly advancing art that I do not wonder that the putting of money into buildings gives one great concern, because there is no knowing at any time but what some electrical engineer, or electrochemical engineer will come along with a process about twice as efficient. This efficiency would threaten to scrap all the processes now in operation. The whole subject appeals to us all as being one of the best applications of modern chemical and electrical science to industry one which has an immense, almost inconceivable, future.

J. L. R. Hayden (by letter): In the discussion of the limitations of the arc furnace process the possible concentrations are calculated on the basis of the thermodynamic equilibrium, though the work of Haber makes it very doubtful whether the arc furnace process is a thermodynamic one.

An extensive series of investigations, which I made some years ago in Dr. Steinmetz's laboratory, led me to the conclusion that in the fixation of nitrogen by the electric arc the conditions of thermodynamic equilibrium are of secondary, if of any, moment; and the process is essentially an electric one. A series of experiments with arcs of different temperature seemed to show no direct relation of the NO concentration to the arc temperature as depending on the arc stream material. In order of their NO producing efficiency, the arc electrode materials arranged themselves in the following order:

Iron: Highest NO concentration,
Titanium,
Carbon,
Copper: Lowest concentration.

While the order of the boiling points of these materials is:

Carbon: Above 3600 deg. cent.
Titanium: About 2700 deg. cent.
Iron: 2450 deg. cent.
Copper: 2310 deg. cent.

Carbon, of the highest arc temperature, is very low in efficiency, while iron and copper, with approximately the same arc temperature, are at the opposite ends of the scale.

With low-temperature arcs, as the mercury arc, it is easily possible to get concentrations above those representing the thermodynamic equilibrium.

From this and other results of the investigation, I am led to the conclusion that the NO production by the electric arc is essentially a dissociation phenomenon. In the arc stream, the molecules of oxygen and nitrogen are dissociated into free atoms, and when leaving the arc stream, these atoms combine with each other by the probability law. As air contains four times as much nitrogen as oxygen, each oxygen atom has four times as much chance to find a nitrogen atom as an oxygen atom, and thus four NO would be formed for every O_2 and in the same manner four N_2 for every NO. The gases leaving the arc stream should, therefore, be a mixture containing 32 per cent NO. As at high temperature the reaction velocity is extremely high, the NO concentration rapidly falls to the low concentration of the thermodynamic equilibrium. The more rapidly the gases are cooled down to the temperature where the reaction velocity is low, that is, the mixture stable, the higher a percentage of NO would be preserved. Also, the lower the initial temperature—that is, the arc temperature—the higher, with the same rate of cooling, should be the NO production. The low-temperature arc therefore should be the most efficient. In agreement with this is the above table, where, with the exception of copper, the materials arrange themselves in their efficiency of NO production about inversely to their boiling points. The abnormally low efficiency of copper may be explained by the tendency to instability of the copper arc.

David B. Rushmore: In all the talk of conservation that has been going on for the last few years, we have had a great deal that was thoroughly high-class and desirable, and a great deal that was not. Practically nothing has been said about the fact that our civilization is absolutely founded on from four to six inches of soil on the surface of this earth, and the conservation of that thin layer is an absolute necessity. We in this country have not yet learned very much about how to do it.

Now, the object we are after, or one of the objects in manufacturing nitrogen products, is not necessarily to make the cheapest fertilizer. What we are after is the cheapest finished product, and in many cases the finished product of one industry is the raw material of another. The finished product of the fertilizer industry is the raw material of the agricultural industry, and that is very little understood. As Mr. Washburn has just said about the manganese sulphate, you used to hear a man just becoming interested in agriculture talk about fertilizing as if it was the simplest thing in the world—you simply analyze an apple on the tree, find what is the percentage of the different elements in it, spread these elements at the root of the tree, and that is all. As a matter of fact, there is a vast deal to learn—how the elements of the fertilizers react upon each other, and react upon the elements that are already in the soil; how they become available for plant life. We must also bear in mind the fact that the operation of fertilizers in a grove of trees must necessarily be intermittent, that it is affected by a certain amount of rainfall and sunshine, which evaporates and washes away the constituents of the fertilizer, and also that the action of bacteria is just beginning to be understood. This leads us to suppose that our present mode of applying fertilizers to plant life is probably extremely crude and inefficient, and that we know but a very small percentage of what ought to be known of the best form in which these fertilizers should be applied.

A point of view not generally understood and appreciated is the close relation between the production, transmission, transportation and distribution of energy and of commodities. Mr. Washburn brought out a point in regard to the necessity of nearby water transportation which is extremely interesting and is very important; and also the point that a great deal of the interest in nitrogen processes is because of the healthy and well-founded search on the part of our power companies for a load for their excess capacity and for an intermittent demand.

If Mr. Washburn's statement in regard to transportation is accepted in a very definite sense, it would mean that water power if removed from water transportation could not look forward to this load, but water powers removed from water transportation are often surrounded by very large agricultural regions. These must be fertilized in some way, and might as well draw on a center of local supply—take it somewhere between the Mississippi and the Pacific Coast—as to ship in fertilizer from one end. I am sure Mr. Washburn, who is most unusually situated as a nitrogen manufacturer and a water-power operator, simply did not go into the detail of his meaning.

To me one of the most interesting things brought out in the first paper is the reason for the limitation of the process along certain lines. I happened to know people who were experimenting—I am not sure how intelligently—on improvements of the arc process; without a knowledge of the fundamental factors that enter into the situation, and without knowing just the part played by the electric field, which has not been mentioned tonight, the temperature and pressure and velocity of change. It seems to me without this knowledge a very great deal of blind and expensive experimenting would necessarily follow. It is not clear to my mind why the electric field, which can work on the oxygen molecule to dissociate the atoms in the form of ozone, and if compressed a little further, as we know, results in nitrous oxid—why that electric field could not be a possible factor in a process of this kind.

Charles A. Doremus: Provost Edgar F. Smith of the University of Pennsylvania has written a book on "Chemistry in America." In that volume he gives three reprints; one a paper by Robert Hare, a member of the Philadelphia Chemical Society, written in 1801. Hare gives a picture of the oxy-hydrogen apparatus and his blowpipe, and it has taken us seventy-five years to come to the practical use of the process of oxy-hydrogen welding and cutting, and the oxy-acetylene process. The second is an annual address by Henry P. Smith, of that same society, delivered in 1798, worthy of reading, as showing the wide knowledge that these men possessed of the possibilities of chemistry in this country and the influence of that science upon the growth of the nation. The last is an address delivered in 1801 by Dr. Felix Pascalis, in which he refers to the manufacture of nitric acid from the nitrogen of the air, by the improved apparatus of citizen Guyton de Morveau.

It has required a world conflagration to make us appreciate our possibilities, and there is no more fertile ground to work on in this country than that which Mr. Washburn has pointed out.

F. V. Henshaw: I ask Mr. Washburn if he will be kind enough to elaborate a little further on the necessities of location. Is the necessity for a cyanamide plant being on tide water, or where there is water transportation, based on the requirements for raw materials, or has it any connection with the shipment of finished products?

Frank B. Washburn: In my reference to the limitations of the interior point of manufacture, I had in mind the manufacturing of ammonia phosphate, which requires not only the raw materials used in cyanamiding, but also phosphate rock. Phosphate rock is found in this country practically in only two places, in the state of Florida and the state of Tennessee. It is a low-grade material, and its transportation by water from Florida is very cheap. Its transportation by rail to the interior is very expensive. If it were purely a question of a cyanamide factory, there are interior points that would serve the agricultural requirements of the neighborhood and environment, just as Mr. Rushmore surmises. Beyond all that, my remarks were affected by the broad plan which those who have given the subject consideration, think must be adopted to make the best success of a modern nitrogen undertaking. It has got to be a case of concentration, of a large organization made up of the very best skilled and selected men that can be found. In anything which has to do with the electric industry, there is a tremendous advantage in manufacturing at one point, because almost every process gives rise to what may prove to be the raw material for an additional process. Therein lies the success for the Germans, and therein lies the handicap of the United States in going into the chemical industry and taking, as many of us have discussed and debated doing, the trade during the time that the German industries are idle.

Therefore, from that point of view we have not considered, and of course could not consider, locating in a great many places. The cost of transportation of raw materials—phosphate rock, for instance—from almost any part of the Atlantic, in fact from down on the west coast of Florida into Canada, by water, is cheaper than the transportation of that same material out of Florida a few miles north of the Florida border by rail. The transportation of coal which is converted into coke has many of the same aspects. The transportation of the finished product has to be done at the cost of handling it and loading it into the ship and out of it, as the boats would otherwise return empty from any large water-power plant having deep sea entrance. Practically the same conditions apply to our investigations on the west coast.

So, as a general statement, the practical thing to do in a great manufacturing industry, employing water power running into the hundreds of thousands of horse power, is to locate within a seventy-five cent barge rate of New Orleans on the Mississippi River system, or upon deep water, or where deep water can be reached readily on the Pacific or Atlantic coast.

F. V. Henshaw: What would be the relative tonnage in the phosphate ammonia process,—the tonnage of the raw material and finished product, 5 to 1, 10 to 1?

Frank B. Washburn: I think in the case of ammonia and phosphate it would be 4 to 1, probably.

Leland L. Summers: I want to answer Mr. Rushmore's question, as it seems to apply particularly to the point I raised: Why is not the electrical effect of the arcing system with its ionizing element, of tremendous importance? The electron effects under partial pressure are very pronounced. The question arises, why should we not use such a process as the arcing system, where there is a tremendous magnetic field distorting the arc, so that the flame expands into a wheel six or eight feet in diameter and sounds like a battery of artillery when you open the furnace? It is amazing that there should not be a more pronounced electronic or ionizing effect. The truth is, at these temperatures dissociation is so active that though you have an electrical effect you cannot remove the product with sufficient rapidity. The final effect in all the arcing processes is due to thermal energy only.

You asked more in regard to ozonizing and low-temperature work. Ozone is produced almost entirely at low temperature. If you use an incandescent wire and liquid air, you can produce ozone, so that you might refrigerate oxygen some time in an active form. You might activate nitrogen by temperature, and hold the oxygen in a more active form, produce chill, and in that way produce a greater effect and be free from this temperature of dissociation. It is entirely theoretical. It has been experimentally done and some interesting results obtained, but I do not know of any actual applications commercially.

Presented at the 306th meeting of the American Institute of Electrical Engineers, Cleveland, O., March 18, 1915.

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APPLICATION OF ELECTRICITY TO THE ORE HANDLING INDUSTRY

BY C. D. GILPIN

ABSTRACT OF PAPER

The paper gives a general description of the typical method of handling ore from the mine to the blast furnace, describing in a general way the machinery used in the different steps of the process. The general principles underlying the application of electric motors to these various types of machines are discussed, as well as the class of motors best adapted to the work and the considerations in regard to the power installation. The essential points to be considered are: 1, the determination of the shortest path over which the ore is to travel; 2, the determination of the characteristics of the loads in moving ore through this path; 3, the designing of the electrical equipment to carry these loads with minimum peak and maximum reliability, and 4, installation of a substation that will handle the load satisfactorily and most economically, considering both demand charges and the total kilowatt-hours used.

IN DISCUSSING the application of electricity to the iron ore handling industry it is the writer's intention to portray in a broad manner the nature of the problems which are encountered, and the general principles which should be kept in view. Detailed descriptions of the method of making the necessary calculations are now available in at least one of the later handbooks, and the electrical apparatus used for this class of work is fully described in the publications of the various manufacturers. It can easily happen, however, that the electrical engineer may lose sight of one or more of the points described herein, or that the purchaser of an ore handling plant may find himself saddled with an equipment for which the cost of power is unduly h.gh.

Before describing the correct methods of applying electrical apparatus to ore handling machinery it will, perhaps, be best to give a brief description of the types of such machines as are in general use. The typical course of the ore from the mine to the blast furnace is as follows, this description applying particularly to the business as it is carried on in the Great Lakes district:

After being mined in the upper lake region, the ore is carried in special hopper-bottom cars to one of the nearby shipping points, where it is dumped by gravity into large bins. These bins are connected to the hold of the vessel by means of spouts, so that loading is accomplished simply and in a very short time. The vessel then carries the ore to one of the ports on Lake Erie or Lake Michigan, where its cargo is taken out by means of large unloaders and is either placed on railroad cars or is stored in a stock pile for future use. After being loaded on the cars the ore is carried to the point of ultimate consumption, where it is usually unloaded by means of a car dumper. At this point two general schemes of handling the material may be used, the first consisting of a movable car dumper which travels along one side of a stock yard, into which it dumps the ore, and the second consisting of a fixed car dumper which dumps each freight car into an electrically propelled transfer car having gates in the bottom especially adapted to allow the ore to run out cleanly. In the latter case the transfer car deposits its load directly into the bins which serve the furnace skip hoist; or, if these bins are already full, the ore may be allowed to fall down an incline into the stock yard, from which it is reclaimed by means of a bucket-handling gantry crane and is placed in the furnace bins as it is needed. In this paper the discussion will be limited to the operations of unloading the boat at the dock and the unloading, stocking and reclaiming of the ore at the blast furnace.

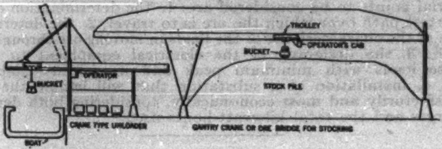

FIG. 1

Fig. 1 shows a side elevation of a dock equipped with one or more crane-type unloaders in combination with a rehandling gantry crane. The unloader is provided with a trolley which runs out over the hatches of the vessel; a clam-shell bucket is then lowered into the hold, and the loaded bucket is hoisted and trolleyed back either to a bin which feeds the freight cars, or to a space in the rear of the unloader, from which it is picked up by a bucket carried on the gantry crane trolley, and is placed in storage. From this storage pile the ore is eventually reclaimed by the stock pile gantry and is loaded on railroad cars. The crane type unloader is essentially the same as the stock pile gantry, and the principles which apply to one will apply to the other.

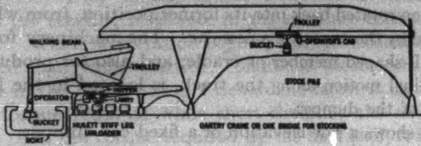
TROLLEY
WALKING BEAM
BUCKET
OPERATOR'S CAB
TROLLEY
STOCK PILE
HOPPER
OPERATOR
LARRY
BUCKET
BOAT
HULETT STIFF LEG UNLOADER
GANTRY CRANE OR ORE BRIDGE FOR STOCKING

FIG. 2

Fig. 2 shows a Hulett unloader in conjunction with a gantry crane. In this type of unloader the bucket is suspended from a walking beam by means of a stiff structural leg, the operator riding directly above the bucket. This leg is held steady by means of an equalizer and may be rotated at will. The walking beam is carried on a large trolley which moves the loaded bucket back over a bin, into which the ore is dumped. From this bin the ore is fed as desired into a larry car, which carries it either to a point above an empty railroad car or else deposits it on the ground in the rear of the unloader, there to be cared for by the gantry crane.

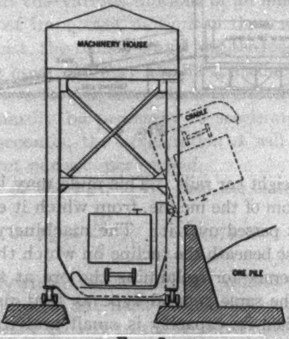
MACHINERY HOUSE
CRADLE
ORE PILE

FIG. 3

Fig. 3 shows the end elevation of a movable car dumper.

With this type of dumper the car is pushed up a short incline by means of the locomotive until it rests on the L-shaped rotatable member. When this member is turned over, the contents of the car slide down a chute into the stock pile, the car being held in place by means of counterweighted clamps. The empty car is then rotated back into its former position, from which it is displaced by the impact of a new car. The machinery for operating the L-shaped member or cradle, and also for producing the longitudinal motion along the track, is located in the house at the top of the dumper.

Fig. 4 shows a side elevation of a fixed car dumper. The car is dumped in the same way as with a movable dumper, but with this type of machine it is necessary to haul the loaded cars up an incline and onto the cradle by means of what is known as a "mule," which consists of a small carriage running on a track between the freight car rails. This mule may be lowered into a pit in the bottom of the incline, from which it emerges after the loaded car has passed over it. The machinery is generally located in a house beneath the incline on which the mule operates.

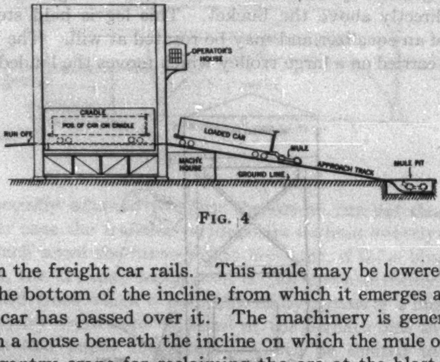

FIG. 4

The gantry crane for reclaiming the ore at the blast furnace is usually of the same general type as that used at the dock, except that when its capacity is small and its span is short, both the operating mechanism and the operator may be located on a fixed part of the bridge. The ropes for handling the bucket are then carried out to a small trolley which is little more than a number of sheaves mounted on a carriage.

In considering the problems to be dealt with it will be found that the forces encountered consist either of gravity, acceleration or friction—the latter being understood to be the force ultimately overcome by the mechanism and not the incidental friction in the train of gears. Both the gravity and friction loads produce a similar effect upon the motor, except that in the former case the motor must resist the force of gravity when lowering by means of dynamic braking. In both cases, however, the tendency is for the mechanism to run at a constant speed as soon as the starting resistance in the armature circuit has been cut out. When acceleration begins to be a considerable part of the total load while starting, conditions become changed, especially in the case where a series-wound motor is used. If the motor torque required while short-circuiting the resistance is greater than the torque required by the final load, it is evident that at the instant when all the resistance is cut out the motor torque may be much larger than is necessary, and will therefore tend to speed up the load until it reaches a point of equilibrium. Where the original accelerating force is high compared to the final force, this process of speeding up may consume a very considerable part of the total time of the trip.

It may be of interest to make a few simple calculations which will show to what extent the force of acceleration must be reckoned with in the various motions of an unloader or gantry crane. The most important motions of these machines consist of the bucket hoist, the trolley travel and the longitudinal travel. Taking first the hoist, we may assume a maximum speed of 300 ft. per min. or five ft. per sec., which is greater than is usually used. It will hardly be necessary to accelerate the bucket in less than two seconds; the acceleration A will therefore equal $5 \div 2$, or 2.5 feet per sec. per second.

If the weight of the load is W, then the force of acceleration

$$= F_a = \frac{W}{g} \times A = 0.078\ W$$

While the flywheel effects of the armature and the hoisting mechanism have not been considered, yet their inclusion would not add very greatly to the required force of acceleration, which is seen to be unimportant compared to the gravity load. For the same reason retardation, if accomplished in a reasonable time, will not add very greatly to the dynamic braking load incident to lowering, unless the lowering speed is allowed to become excessive.

Trolley speeds may vary from 200 ft. per. min. for a Hulett unloader to 1200 ft. per min. or even higher, for high-speed gantries having very long spans. Since with a trolley mechanism it is essential to get under way as quickly as possible, the relation of the acceleration force to that of wheel rim friction may be stated as follows:

Using W as the weight of the combined trolley and load, and a value for A of 2.5 ft. per sec. per second, (which experiments by the writer seem to indicate as a maximum value considered comfortable by the operator), then

$$F_a = \frac{W}{g} \times 2.5 = 0.078\ W$$

The average wheel rim friction load may be roughly taken as 25 lb. per ton. Therefore,

$$\text{Friction force} = F_f = \frac{25}{2000} \times W = 0.0125\ W$$

By combining these two equations it will be found that

$$F_a = 6.2\ F_f$$

It is obvious that motors for handling loads of this type must have a very high peak capacity, and in case they are of the series-wound type the final speed of the mechanism will very greatly exceed the speed attained when the last section of resistance is cut out.

To determine the distance traveled and the current consumption at any instant, for a trolley mechanism driven by a series-wound motor, it is necessary to use a step by step method, assuming a series of constantly decreasing torque values on the characteristic curve of the motor, thereby determining the average available accelerating force for each increment, and consequently the time necessary to accelerate through the increment of speed. This method has often been fully described, but a brief outline of it may be of interest.

After assuming the trolley gearing, a constant between torque and force and between trolley ft. per sec. and armature rev. per min. must be worked out. T_1, which represents the average torque while short-circuiting resistance, will be obtained by combining friction torque T_f and acceleration torque T_{a1}, the former being calculated from the wheel rim friction force F_f and the latter being derived from acceleration force F_{a1}, which in turn should be calculated from the highest value of acceleration that the operator can comfortably stand. By the use of the characteristic curves of the motor the value of the motor rev. per min. can be found for the torque value of T_1, and from this can be derived the trolley velocity V_1. Then, if A_1 is the value which has been chosen for acceleration while resistance is being short-circuited,

$$\text{Time} = t_1 = V_1 \div A_1$$

$$\text{Distance} = D_1 = 1/2\, t_1 \times V_1.$$

T_2 is next arbitrarily assumed on the motor curve together with its corresponding value of V_2. Then,

$$T_{a2} = T_2 - T_f, \quad F_{a2} = kT_{a2}, \quad \text{Average } F_a = \frac{F_{a1} + F_{a2}}{2},$$

$$\text{Average } A = \frac{G \times \text{Average } F_a}{W}$$

Also,

$$t_2 = \frac{V_2 - V_1}{\text{Average } A}, \quad D_2 = \frac{V_2 + V_1}{2} \times t_2$$

In this way a curve may be plotted with time as the abscissa and speed and the distance traveled as the ordinates. Horse power and amperes may also be included by reading the motor curve for the various values of T.

Retardation should be taken at about the same value as was figured for the initial acceleration during the short-circuiting of the resistance.

In considering the longitudinal motion, which is used quite infrequently, it is evident that rapid acceleration is not at all important. The longitudinal speed will seldom exceed 120 ft. per min. or two ft. per sec.; if this speed is taken as the value attained when the resistance is all cut out, and if the latter operation consumes four seconds, the value of A will be 0.5 ft. per sec. per second, which will give a value for F_a of approximately 0.0155. Allowing 40 pounds of wheel rim friction per ton, owing to the fact that the ratio of wheel to axle diameter is generally small and the lubrication not always of the best, F_f will have a value of $0.02W$. Therefore,

$$F_f = F_a \times \frac{0.02}{0.0155} = 1.29\, F_a$$

As a matter of fact it is usual to provide a longitudinal travel motor capable of propelling the machine against a 10-lb. wind pressure—a load which will usually equal the friction load or even exceed it by 50 per cent. During ordinary operation, therefore, there will be plenty of motor capacity for acceleration, but the peak to be carried when starting against a heavy wind should be carefully investigated.

For movable car dumpers, unloaders and gantry cranes of short span, the longitudinal travel motor is almost invariably mounted in a house somewhere along the bridge structure, the power being transmitted to at least half of the wheels of each truck by a system of spur and bevel gears. In this case the operator is often located close to the mechanism, which is usually supplied with a mechanical brake which may be released only by the application of the operator's weight. A brake of this nature can be applied gradually, thus avoiding the shock to the mechanism consequent to the sudden application of a solenoid brake.

On long span gantry cranes it is often desirable to place one or more motors on each truck in order to avoid the expense and the friction losses incident to the squaring shaft used with a single motor bevel gear drive. With this construction it has been found that there is little tendency for one end of the crane to run ahead of the other, no matter what type of motor may be used. Separate controllers are of course necessary for each end of the crane, and safety devices should be provided to prevent the structure from being twisted in case one end gets too far ahead of the other. Moreover the motors must be supplied with solenoid brakes, which should preferably be of a kind in which the full braking force is not applied suddenly.

In the foregoing calculations on acceleration no consideration has been given to the flywheel effect of the armature. Fig. 5 shows a curve in which the flywheel effect [*Wt.* × (rad. gyr.)^2] of a number of armatures has been plotted against their horse power. The values given are obtained by averaging the actual values for several lines of standard d-c. mill motors. A curve of this kind may be useful at times for making preliminary calculations.

The best plan for estimating the effect of the armature inertia is to translate the weight of the armature into terms of the moving load. Since in the case of a trolley motion the speed of the series motors is constantly varying, a gear ratio of some sort must be assumed before any calculations can be made. As the equivalent weight of the armature is given at one ft. radius, the speed of this weight will equal 2 π rev. per min.; and since by the assumption of a gear ratio there has been established a definite relation between motor rev. per min. and load feet per min., the armature weight may be stated in terms of load weight by multiplying it by the square of its equivalent speed and dividing by the square of the load speed. Owing to the fact that when figuring acceleration, the accelerating force required at the load must be divided by the efficiency (expressed as a decimal) in order to allow for the losses in gearing, it will be necessary to multiply the equivalent motor weight by the efficiency before adding it to the load weight, since the accelerating force for the armature does not have to be transmitted through the gearing. With the usual type of trolley used in ore handling machinery, the acceleration of the trolley motor armatures may amount to ten per cent of the total. When calculating the capacity of the motor for any kind of work with which the engineer is not familiar, it is well to look into the matter of armature acceleration.

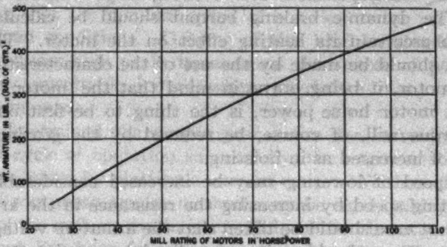

FIG. 5—COMPOSITE CURVE OF FLYWHEEL EFFECT OF THREE DIFFERENT MAKES OF MILL MOTORS

It has been seen that in all trolley motions acceleration is the main feature, while in longitudinal traverse motions it is less important, and in hoisting motions it is of little moment. Transfer cars in this respect may be classed with the trolleys, while the cradle turning motion of the usual type of car dumper is equivalent to a hoist. The mule haulage of a fixed car dumper is a combination of the two types of load, since the acceleration of the car to a speed of anywhere from 200 ft. to 400 ft. per minute is a considerable item. This acceleration, however, takes place before the car gets well onto the grade, so that it is not ordinarily combined with the gravity load. It may be added that this mule haulage motion is one in which the writer has found that the flywheel effect of the armatures is a matter worth figuring, owing to the fact that the mule is run down the grade at a much higher rate of speed than normal and must be retarded very rapidly as it enters the mule pit.

Referring again to the subject of hoists, the engineer should give due consideration to the question of lowering, which in any bucket handling device is likely to require a very considerable negative force to be exerted by the hoisting mechanism. The question of dynamic braking has been gone into so often and so thoroughly that the writer will merely say that it is practically indispensable for lowering large buckets and the like. The dynamic braking current should be calculated in order to ascertain its heating effect on the motor. This calculation should be made by the use of the characteristic curve of the motor, it being borne in mind that the motor torque, and not motor horse power, is the thing to be first obtained. This torque will, of course, be reduced by the gearing losses instead of increased as in hoisting.

The speed of lowering may be increased considerably over the hoisting speed by increasing the resistance in the armature circuit, but care should be taken that the armature voltage does not rise very much above its normal value—a point that may easily be checked after the dynamic braking current has been calculated. While the current produced by the armature may be returned to the line, yet this requires a more complicated form of controller than is usually used, and is moreover generally practicable for one speed of lowering only. Up to the present, the great effort in the ore handling industry has been to secure reliability rather than any nicety of current economy and in the future reliability will still be the main consideration, since delays may possibly tie up a ship or even a blast furnace.

In entering upon the consideration of an ore handling problem, the electrical engineer must have a fairly definite knowledge of how much ore it is required to handle per hour, per day and per year. The hourly rate will affect the gearing and also the peak load; the daily rate will affect the heating of the motors; while the yearly rate will determine the number of kilowatt-hours on which figures for power are to be based.

After determining the minimum time in which the average round trip or cycle of a given machine is to be made, the engineer should draw a mental picture of the shortest path for the ore to travel. The hoist and trolley motions should then be geared so that when operating as nearly simultaneously as possible they will carry the ore through this short path. In other words, it is poor engineering to install a hoist motor which will raise the load to the required height long before the trolley has reached the end of its travel. A rather more common error is to gear the trolley motion entirely too high, so that it is necessary to hoist for a considerable length of time before starting to traverse the trolley. Occasionally trolleys are so improperly geared that they may cover almost half their average travel before the resistance is all cut out of the armature circuit. This is probably due to the fact that some designers persist in believing that the nominal speed of a series motor prevails under all load conditions. Gearing of this kind overloads the motors, produces high peak demands on the source of power, and is very unsuitable indeed where there are many short motions to be made.

Having determined the proper gear ratios for carrying out the desired cycle of operation successfully, the engineer should check up his motor by plotting a current curve. With enclosed motors the root-mean-square method may be used, taking the total time of the cycle as the divisor. This method is not strictly accurate, but has been found to be a good guide. The only scientific way that the writer has seen to determine the heating of an enclosed motor is one which has been recently brought out by one of the large electrical companies. With this method the radiating capacity in watts for each frame is given and curves are furnished showing the motor loss in watts for various loads. The average watts which must be dissipated by the motor for a given cycle can thus be determined.

With open type motors the root-mean-square method is also generally used for figuring the heating, but it should be remembered that this type of motor is more dependent on the rotation of its armature for heat dissipation than is the enclosed motor. The writer has been accustomed to estimate the equivalent value of the time when the motor is accelerating or retarding as being equal to two-thirds of the full-speed running time, the time at rest being taken as equal to about one-third of the running time; thus if the cycle of operation of a given motor be 60 seconds, of which 30 seconds are consumed in running at full speed, 12 seconds in accelerating and retarding, while for 18 seconds the motor is at rest, then the total equivalent time will be 30 seconds plus 8 seconds plus 6 seconds, which equals 44 seconds. The latter value then would be used as the divisor under the radical in determining the r.m.s. current.

While mill motors are usually rated on the horse power which they will develop for one hour with a rise of 75 deg. cent., open type motors may either be given their continuous rating at 40 deg. cent. or may have a nominal rating of about 50 per cent above their continuous capacity. The nominal ratings of motors afford a basis of comparison between similar motors of the same type, and give some idea of the commutating capacity of the motor. They are not particularly valuable in any other way, as it is the continuous heat-dissipating ability of the motor which is essential for severe all-day operation.

With most ore handling machinery the limitations of space do not permit the installation of the ordinary open type motor; moreover the mill type of motor is generally preferable on account of its high momentary overload capacity and its sturdy mechanical construction. It will often be found, however, that an enclosed motor of this type, while in other ways ideal for the work, may have insufficient heating capacity for all-day service. In such cases, if the motor can be protected, a semi-enclosed type of frame may generally be obtained, which will give a greatly increased heating capacity. With machines of the car-dumper type, where there is plenty of room in the machinery house, open type three-bearing motors are commonly used.

After the engineer has chosen his motors and plotted his current curves for each of the essential motions of his ore handling machines, the curves for one machine should be combined to show the current input to the machine for its average cycle, care being taken not to include dynamic braking current. The current curves for the other machines should then be combined with the first one in order to find the characteristics of the load for the total plant. Where there are two unloaders at work the writer generally assumes that an average condition will be for one unloader to be a quarter of a cycle in advance of the other, this being a mean between the condition where the machines are in synchronism and where they are half a cycle apart. Due provision, however, must be made for handling an occasional exceptional peak due to simultaneous operation of the important functions.

Where there are a number of unloaders working together the writer generally figures that half of them may be in synchronism at the same time. This is a question to answer which the engineer must use his best judgment, combined with considerable patience in trying out various combinations of load cycles. It is obvious, however, that the peak loads of a number of machines will very seldom come at the same time; in such cases it is better to let the circuit breaker open than to provide the necessary equipment for handling such an unusual condition.

With an installation which obtains its current from the power house of a large steel mill, the question of peak load is not very serious. In the case of an isolated dock, however, a complete generating station must be built, or else power must be purchased—and in both of these cases the form of the load curve is very important. It will usually be found that the public service corporations will supply power at a cost which is slightly under the cost of generating the power at the dock, if the proper allowances be made for depreciation, possibility of accidents, etc. Since purchased power is almost invariably in the form of alternating current, the possibility of using a-c. apparatus is a question that is always with us. Where machines of the type of the Hulett stiff-legged unloader are used—and these machines unload most of the ore on the Great Lakes—alternating current is out of the question. The Hulett machine owes much of its success to the fact that the operator is in close proximity to his work, and can gage distances to within a very few inches. Without the use of a delicate system of control, which is possible only with direct-current dynamic braking, this advantage would be largely lost.

For transfer cars, direct current is almost essential, since such cars are best propelled by railway or mine type direct-current motors. An a-c. motor of similar size, even if designed for axle suspension, would hardly have sufficient torque to obtain rapid acceleration.

Bucket handling gantry cranes and crane type unloaders can use alternating current if their hoist motions are provided with dynamic braking. This dynamic braking is obtained by exciting one phase of the stator from a small low-voltage direct-current motor-generator set, the resistance in the rotor circuit being changed to obtain the various changes in speed. This system is not absolutely reliable, however, as the dynamic braking torque depends very considerably on the proper combination of rotor speed and resistance, and is likely to be lost almost entirely if too rapid a retardation is attempted. The trolley travel motors are also not nearly as satisfactory, since all the acceleration must be obtained while short-circuiting the starting resistance, whereas with a series d-c. motor this operation will probably bring the motor only up to half speed, the rest of the increase of speed being attained after the resistance is cut out. The a-c. trolley motor, therefore, may often be badly overloaded while starting, yet after acceleration it may be underloaded to such an extent that its power factor is very bad indeed.

The writer believes that a fairly successful a-c. car dumper may be designed, although it would cost more than a d-c. machine and would undoubtedly give more trouble. There might be cases, however, where the installation of such a machine would be justifiable, provided that the required rate of handling ore were not very high nor the continuity of operation very important.

It should be borne in mind when comparing a.c. with d.c. that while mill type motors may be obtained for 25-cycle circuits, the 60-cycle motors obtainable are all of the open type, requiring protection from the weather; these motors should usually be provided with an outboard bearing when their ratings exceed 25 horse power. The number of parts of the control systems should also be considered.

Before the final decision has been made as to whether alternating or direct current is to be used, the power contract offered should be carefully inspected. This contract will invariably provide a charge for each kilowatt of demand, this charge being usually from one to two dollars per month. The way the demand is figured, however, varies quite widely with different power companies; with some it is the shortest peak which can be detected by a curve-drawing instrument, while with others it is the average of the load for the worst hour during the month. Other companies base their demand charge on the capacity of the transformers in the substation, but in this case they sometimes allow themselves the option of installing a curve-drawing instrument, determining their charge by a certain per cent of the indicated peak for a given time if such peak shows a higher monthly charge than could be calculated from the rating of the transformers.

Where the ore handling machinery is operated by a-c. motors there is little that can be done toward reducing demand charges, but if a substation with motor-generator sets or synchronous converters is installed, there is a possibility of diminishing these charges under certain conditions. When the demand is based on a peak lasting five seconds or less, a synchronous converter plant with a flywheel balancer is usually applicable. This flywheel balancer is a shunt-wound d-c. machine which is connected across the busbars, and which sometimes acts as a motor and at other times as a generator. It has coupled to one end of its shaft a laminated flywheel running at very high speed. When the peak load comes on, the regulating apparatus strengthens the field of the balancer so that it generates direct current into the busbars until its speed —and consequently that of the flywheel—has been reduced to the value corresponding to the strengthened field. After the peak load is over, the field is automatically weakened and the balancer gradually brings the flywheel up to its former speed.

The synchronous converter substation, provided where necessary with a flywheel balancer, will generally be found to be cheaper and more economical of power than a motor-generator station, the flywheel equipment in both cases being equal. The motor-generator set, however, may be better in certain cases. For one thing, the direct voltage can be more easily controlled; but the principal advantage is in cases where the demand charge is based upon the rating of the connected apparatus. Since the size of the d-c. machine will almost always be governed by its commutating capacity, it is evident that the a-c. apparatus supplying it with power may have a much smaller continuous rating. Now, a comparatively small flywheel will prevent the motor of the motor-generator set from pulling out of step, and even if the speed falls off considerably a voltage regulator can be used at the direct-current end if a steady voltage is necessary. An installation of this kind is, therefore, worthy of consideration under the proper conditions.

The meter charge for power furnished is often graduated, decreasing as the quantity of power consumed increases; in some cases the rate for the last gradation may be as low as 0.5 cent per kw-hr. and under favorable circumstances the combined peak and meter rate may be less than one cent per kw-hr. While it will usually be found that any economies in power consumption affect the lower rather than the higher power rates, still in certain instances such economies may tend to reduce the demand charge. For instance, series-parallel control will reduce the starting peak of a trolley mechanism or a transfer car very considerably, and may also be profitably employed in mechanisms such as those of car dumper cradle hoists or mule haulages; thus the demand charge for the whole installation is lowered. This system is not always adapted to bucket hoists, however, as there is usually one independent motor and controller for each of the two parts of cable by which the motion of the bucket is controlled. In case series-parallel control should be used with a hoist motion, care should be taken to choose a type which passes from series to parallel smoothly. This point is particularly applicable where compound-wound motors are used, owing to the back e. m. f. which is always present in the moving armatures of such motors.

When choosing the motors for ore handling equipment, preference should be given to the mill type where the room is restricted and where momentary overloads are severe and often repeated. Enclosed crane motors are satisfactory in the smaller sizes for less severe and less frequent service, while open type motors are excellent for service of the car dumper type where heating is quite a factor but where overloads are not very severe. As stated before, either railway or mine type motors may be used with transfer cars, but if the latter are installed they should probably have a better margin of safety than the former, as they are very compactly built. Mine motors are, however, very convenient in some cases, because they are designed for low-speed, high-torque work.

With regard to the type of field winding, experience has shown that the series-wound motor is admirable for almost all classes of ore handling machinery. Occasionally it is necessary to use a compound-wound motor where there is danger of a runaway, but the shunt field, especially in the restricted space available in a mill motor, is a distinct point of weakness with regard to insulation.

It is the practise at the present time to install contactor type control for every motion of any importance whatever. This type of control pays for its increased cost, not only in decreased depreciation and maintenance, but also because the operator need pay so little attention to it that he is free to concentrate his mind upon his work.

With hoist controllers it is usual to give the operator at least one power point in the lowering direction so that he may pay off slack in case the negative load is absent. The other steps may all be dynamic braking. In any case, the armature and field should at all points be included in some kind of a closed circuit with one another so that there will be no possibility of a runaway.

Trolley controllers usually do not include dynamic braking, and may or may not have series-parallel control, although the use of two or more motors on large trolleys is universal in order to secure sufficient traction. If dynamic braking is desired, the motor fields should be separately excited so that the motors will act as shunt generators. If the connections are such that the motors are turned into series generators, not only will the armatures have to be reversed for dynamic braking to take place, but the braking itself will be very uncertain. At low speeds it may entirely fail to materialize, while at high speeds it may be over-severe. Probably a good air brake equipment on the trolley is preferable to dynamic braking, unless the operator is located at a distance from the mechanism. It should be remembered also that it is quite safe to "plug" the trolley motors if a point of high resistance is available to limit the consequent rush of current.

Motor-driven apparatus combined with contactor-type control is particularly suited for automatic travel limitation. Systems of this kind vary from the simple cutting off of power, which is all that is necessary for a bucket hoist, to the slowing down by armature shunting and the subsequent re-acceleration, which are automatically obtained, in some car dumpers, just as the mule engages the loaded car. Dynamic braking, if desired, may also be obtained automatically by means of a limit switch.

Where low speeds are desired with light loads, armature shunting is generally used, but where used for retardation one point is often rather unsatisfactory, as it is likely to be too violent during the start and too weak toward the end. If series-parallel control with compound-wound motors is used, half speed may easily be obtained, whether the load is light or heavy; but the control should be such that resistance is inserted momentarily into the armature circuits during the transition from parallel to series, so that the current generated back into the line will not be excessive.

Solenoid brakes are used almost universally in ore handling machinery where there is any kind of a gravity load. Possibly the best friction surface for such brakes consists of some one of the several asbestos compounds which may be obtained, although iron shoes bearing on iron brake wheels are often used. Solenoid brakes are generally mounted on the armature shaft of the motor, but in very important mechanisms where it is feared that there is a chance of the motor pinion failing, the brake wheel may be placed on the countershaft. The series type of winding is preferable as far as strength of insulation is concerned, but is impracticable where the load is likely at times to decrease to a very low value. In such cases a shunt winding should be used, a separate contactor on the controller usually being necessary to handle its circuit.

While there are several lines of excellent motors on the market, detail improvements are still possible in some directions. The writer's experience is not nearly so extended as that of one engaged in maintenance work, but the results of his observation would indicate that the following points are worth watching:

Insulation of fields, especially where shunt windings are used.

The mica in the commutator, which in many cases should be undercut.

The construction of the armature spiders and the bracing of the rear ends of the armature coils, which are subjected to great strains where motors are allowed to over-speed and are then suddenly retarded.

In spite of the use of commutating poles, sparking at the commutator is not uncommon. Where this occurs from extremely rapid changes in loads, the trouble may possibly be that the solid cores of the commutating poles do not respond as quickly to the magnetomotive force as do the laminated cores of the main poles. In other cases, sparking and commutator heating may be traced to the vibration of the gears. The use of cut herringbone gears in such cases often leads to a remarkable improvement in commutation. Indeed, it is likely that the future will see a very wide use of these gears in the ore handling industry. When properly set up their life is long, their efficiency high, and noise is almost absent. The makers of these gears recommend that the pinion be mounted between two independent bearings, with a connection to the motor shaft by a flexible coupling. While this is doubtless the ideal method, yet in many cases where these gears have replaced spur gears without any other change having been made, they have given satisfaction. Pinions should be set up, however, with due regard to a possible magnetic longitudinal pull of the motor shaft.

With regard to the electrical troubles which may be experienced with an ore handling plant as a whole, the writer has found that most of them come from a piecemeal method of design which often prevails. The purchaser, for instance, will sometimes buy the unloading equipment from one concern and the stock pile gantry from another, while he himself will put in the substation apparatus and the contact rails. In this way the various parts do not always match as well as they should, and in some cases the substation is not of a design which is adapted to keeping the power bills at a minimum.

A consideration of the foregoing will perhaps make it apparent that the following points are essential to a well-designed plant:

The calculation of the shortest path through which the ore is to travel.

The determination of the characteristic of the loads incident to moving the ore through this path at the proper number of trips per hour.

The provision of electrical equipment capable of carrying these loads with a minimum peak and a maximum of reliability.

The installation of a substation, if power is to be purchased, that will handle the load satisfactorily and will also be best suited to the power contract, considering both demand charges and the total kilowatt-hours to be used per year.

DISCUSSION ON "APPLICATION OF ELECTRICITY TO THE ORE HANDLING INDUSTRY," (GILPIN), CLEVELAND, OHIO, MARCH 18, 1915.

D. B. Rushmore: In the handling of ore, as well as in the handling of a great many commodities by mechanical means, it is very interesting to consider the economic reasons for the application of the electric motor.

The function of the electric motor in coal and ore handling is a little difficult to explain unless one can picture in his mind the different operations. The actual handling of the ore is a comparatively small part of the iron and steel industry. It is one of the great number of links in the process of steel manufacture, and it is evident, even in the process of handling the ore, a large series of operations is involved. The cost of handling the ore is one factor; the time involved is another.

Consider, for example, the boats plying back and forth on the lakes and the old ways of unloading them with wheel-barrows, the length of time they were tied up to the docks as compared to the present methods of unloading. Even if the present way was more expensive per ton than the old one, it would still pay on account of the increased capacity of our modern equipments.

There are a number of very interesting points brought out in Mr. Gilpin's paper worthy of discussion. It would be interesting to know the cost of the different operations. Such costs, of a very great accuracy, are possible to be obtained with the electric motor equipments, and by a careful analysis of the costs there is possible a greater opportunity for saving by increasing the capacity than in any other field.

D. M. Petty: I would like to ask about the relative cost of a motor-generator set and synchronous converter for substations of this kind. I suppose the author has in mind an induction motor-driven generator in connection with a flywheel. I would like to know whether that is more efficient than a synchronous converter combined with a balancer set and if the author has any idea of the relative first cost; also if any of the members have had much experience with series motors, both interpole and non-interpole. There has recently come to my attention the possibility that the interpole series motor is not doing dynamic braking as satisfactorily as the non-interpole motor.

R. H. McLain: Regarding the method of figuring motors described, I think it might be interesting to some of those present to refer to a paper which I prepared last June for the Detroit meeting in which I pointed out a method for determining the work on trolley motors and determining the proper method to gear them. Therein are certain curves plotted between time and distance for various maximum gear speeds, and I believe their use would eliminate a lot of the tedious work in figuring out proper trolley motors so as to take full advantage of their accelerating possibilities. I won't go into the details of that now, but it is explained in my paper.

There is a word I would like to say about heating in motors. I think it is the general experience that an enclosed motor of the same weight and approximately the same cost as an open motor will do the same work for possibly an hour, or something near that, which an open motor will do continuously. It depends somewhat on the ventilating characteristics, the speed of the motor and other things, but that is a fair rule for a lot of the motors used in this kind of work. It is certainly an advantage to use the open motor for this reason, even going to extra expense for protecting the open motor in order to permit it to be used where possible.

About the root-mean-square method of choosing motors, I think it is about time that this method was eliminated except for merely approximate work, because the losses of a motor do not make a perfect parabola, and that assumption is what the root-mean-square method depends on. Furthermore, the dissipating effect of a frame varies, whether it is enclosed or open, with the amount of windage inside of the motor, also whether the motor is turning over or standing still. An enclosed motor will have a smaller difference of temperature between its frame and its windings if the motor is running and keeping the frame hot, so to speak; for with the motor at standstill, the heat inside can not get out so well. A great deal of work has been done along the line of determining just what motors will do under these varying conditions and it is actually true that, because of the expertness that bridge builders have arrived at in the figuring of their duty cycles, it is possible to predict that a certain motor will not exceed a certain temperature rise. You can also predict the temperature it will attain on a complicated duty cycle.

I am sorry that the author did not go further into the analysis of costs on some of these a-c. problems, especially the a-c. car dumper on low speed. We are told that for most hoist work, the a-c. outfit would cost less than a d-c. outfit. In mine hoists, a-c. motors are used to great advantage and I would like to ask, if the author has time, that he go somewhat more closely into the analysis of a-c. car dumper costs.

H. D. James: In the past electrical engineers responsible for electrically driven apparatus have had trouble because of the careless work that has been done in the selection not only of the mechanical parts, but also of the electrical parts.

I wish to read one portion of Mr. Gilpin's paper.

"With regard to electrical troubles which may be experienced with an ore handling plant as a whole, the writer has found that most of them come from a piecemeal method of design which often prevails. The purchaser of machinery for a dock, for instance, will sometimes buy the unloading equipment from one concern, the stock pile gantry from another, while he will put in the substation apparatus and the contact rails himself. In this way the various parts do not always match as they should, and in some cases the substation is not of a design which is well adapted to keeping the power bills at a minimum."

I might go further and say that very often the purchaser buys the several parts of an electrical equipment from various concerns without giving each concern the necessary information regarding the other apparatus, and sometimes it is very difficult to get that apparatus assembled. I would like to speak of an incident that happened some eight years ago. The United States Government found that it had a great deal of concrete to handle in the Panama Canal and at either end it adopted two methods of handling the materials for making this concrete. At one end Mr. Gilpin did the engineering work on the outfit and it was so well done that the engineer in charge of that work told me there was very little trouble throughout the handling of that concrete. The trouble with the handling at the other end was not with the scheme, I am satisfied. It was because of the lack of proper engineering in the working out of details of the scheme. I mention this fact to show that in one case an electrical equipment was condemned and in the other case it was praised. The equipment was furnished by the same manufacturing company and I believe the large difference was in the engineer who designed the apparatus.

Mr. Gilpin speaks about interpole motors and also a question has been raised about interpole motors and dynamic braking. I think a great deal of the criticism of the interpole motors has been unjust. The interpole motor is a specialized design. It can be designed to handle dynamic braking even better than the non-commutating pole motor, but you can't go to the shelf and take an interpole motor designed for continuous operation in one direction and apply it to dynamic braking. It is only fair to the manufacturer of that motor to tell him what you are going to do with the motor and get his recommendations.

In reference to motor-generator sets and synchronous converters, I think that it is largely a question of charging for power. Our central stations are becoming more reasonable in their demand because they realize the advantage of these all-day loads; but the method of measuring power is a considerable handicap today. I believe that advances are being made and I hope in the near future we will have a better method.

H. F. Stratton: I would like to see a definition of the limits of successful commutation of mill motors. The processes of acceleration, reversal and dynamic braking constitute the majority of the operations of mill type motors. In all of these operations, current peaks must be employed and in order that time may be conserved to a reasonable extent the peaks should be higher than the normal full-load rating of the motor. Complete and definite information is available as to the characteristics of the motor insofar as heating, torque, speed, efficiency, etc., are concerned; but it has been my experience that these characteristics frequently are of less importance than the ability of the motor to commutate. I know of no definite information which will enable anyone to say under what conditions of speed, how much current may be successfully commutated on any given type of mill motors. This lack of information does not involve merely a theoretical demand. It seems to me that, to make the information complete in regard to the application of mill motors, definite information as to commutating limits is fully as important as the information in regard to heating, torque, speed, friction and so forth.

R. R. Selleck: Mr. Gilpin laid particular stress on the proper selection of the form of electrical energy which should be used for coal and ore handling machinery; that is, whether it should be alternating or direct current. This is a very troublesome question to every one who has anything to do with the designing of coal and ore handling machinery. The electrical engineering problems involved in coal and ore handling are special, and require experience along that particular line of work, but the builders of electrical apparatus very often in their frantic attempts to get business will take a stand when they are not familiar with all of the conditions which must be met in a particular application and thus sometimes may advise a customer wrongly. Personally, I agree with Mr. Gilpin that a-c. motors are not adapted for high-torque work, such as found on coal and ore handling machinery; but of late there has been considerable argument on this point and, of course, the question always resolves itself into which form of electrical energy will prove the most economical, notwithstanding the fact that Mr. Rushmore has stated, that all these things could be reduced to a mathematical formula. However, there may be a difference of opinion in the assumptions made, and sometimes using one man's opinion as a basis it will figure out that alternating current is the better proposition, and using another man's opinion, it will figure out that direct current is the better proposition.

D. M. Petty: The question with regard to interpole and non-interpole motors is not how an interpole motor should be built, but refers entirely to the present mill motors as they are built.

J. C. Lincoln: I would like to ask something of the details of the method of obtaining the braking in alternating-current motors. I understand you to say that a small motor-generator is provided and direct current is introduced into one phase. I would like to get some of the details of how the rest of the braking process is handled.

As stated in the body of the paper, the motors considered are not over 15 or 20 h.p., used on freight elevator work and for small hoists. On these motors, the important consideration is not efficiency, but reliability, simplicity and freedom from line disturbance.

I will agree with Mr. James that when we get into work where larger motors are used and where efficiency of the motor becomes an important consideration, the high-resistance squirrel cage motors I have described are not the best thing that can be used. On the other hand, I am sure Mr. James will agree with me that for the type of motors considered in the paper, the squirrel cage motors, from a practical standpoint, have decided superiority over the wound-rotor type. The paper makes it clear that the torque per ampere is higher in the squirrel cage motor than it is in a wound-rotor motor when lifting the same load. Therefore, from the standpoint of the central station man, assuming that the motor must exert its maximum torque, the squirrel cage motor will produce less line disturbance than the wound-rotor motor when doing the same work.

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LINE DISTURBANCE CAUSED BY SPECIAL SQUIRREL CAGE AND WOUND-ROTOR MOTORS WHEN STARTING ELEVATORS AND HOISTS

BY J. C. LINCOLN

Abstract of Paper

The author examines the cause of line disturbances in starting hoists and elevator motors and draws comparison between the performance of wound-rotor motors and squirrel cage motors of a special design for elevator service. Diagrams are given showing graphically the current required for each type of motor to produce a given torque, and the method of control required by different types of motors is also considered. The performances of both types of motors at maximum, ordinary and light loads are compared.

THERE IS a widespread opinion among the engineers of many public service companies furnishing electric power, that wound-rotor motors are inherently superior to squirrel cage motors for hoist and elevator drive, and this is shown by rules issued by some of the larger companies restricting the amount of maximum current that may be supplied to squirrel cage motors, while the restrictions imposed on wound-rotor motors are much less rigid. The object of such regulations on the part of public service companies is to minimize line disturbances and provide as good voltage regulation as possible under the actual conditions of service.

The object of this paper is to examine the causes of line disturbances in starting hoist and elevator motors and to determine, if possible, if the preference for wound-rotor motors for such service is well founded.

Hoists and elevators are so generally constructed with a worm to which the motor is directly connected, engaging a worm wheel to which the load is attached, that only this type of mechanism will be considered in this paper.

There is a rather remarkable lack of exact knowledge among the builders of hoists and elevators as to the amount of torque actually required to start the load as compared to what would be required if there were no friction. The amount due to friction is assumed by many of the elevator builders to be 50 per cent. To put this in concrete shape, let us assume that an elevator builder has received a contract for an elevator in a district where only a-c. power is supplied, which has to lift a load of 3000 lb. at a rate of 100 ft. per minute. He will figure the weight of the car and provide counterbalance for it, and then, in addition, will provide counterbalance for part of the load. Usually about 40 per cent of the load is counterbalanced. To put it another way, the ordinary load is assumed to be 40 per cent of the maximum, and at this load the weight of the car and load together equals the counterbalance, so the power required by the motor at this load is zero, except for friction. At maximum load, this will give a net load to be lifted of 1800 lb. and the net work done will be 1800 × 100 = 180,000 ft-lb. per minute or 5.45 h.p. The elevator builder would double this for friction, making 10.9 h.p. and then, if he had figured on a close margin of profit, would probably use a 10-h.p. motor. He knows that all motors are capable of some overload and he trusts that the overload capacity of the motor, and the fact that his particular machine has "very little friction", will enable him to lift the maximum load. Suppose the motor has a maximum torque corresponding to twice the normal rating, then starting efficiency would have to be

$$\frac{5.45}{2 \times 10} = 27 \text{ per cent in order that the 3000 lb. may be lifted.}$$

An experience with a number of different machines built by a number of different makers shows that the starting efficiency is from 15 to 20 per cent. The starting efficiency is determined as follows:

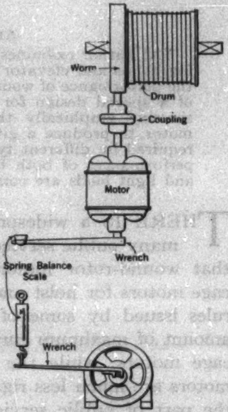

FIG. 1

Fig. 1 shows an elevator in outline, the winding drum, the worm under oil, the coupling, the motor, a pipe wrench fastened to an extension of the motor shaft (or to the worm shaft near the coupling if there is no shaft extension on the motor), and a spring scale or balance attached to the handle of the wrench, say 24 in. from the center of the motor shaft. Full load is now put on the elevator and the brake lifted off, and the spring balance lifted until the motor shaft moves in such a direction as to lift the load. This test is repeated at say ten or twelve points in a revolution of the motor shaft and the maximum lift on the spring balance is noted. From this maximum is deducted the dead weight of the wrench handle, and the balance is the net force required to start the load. Let us assume that the synchronous speed of the motor is 900 rev. per min. and that the net lift was 88 lb. The horse power developed at 900 rev. per min. would be

$$\frac{900 \times 88 \times 2 \times 2\pi}{33{,}000} = 30.2.$$

The useful work done at 900 rev. per min. is 5.45 h.p. The required starting torque corresponds to 30.2 h.p. at 900 rev. per min. The starting efficiency in this case is then $\frac{5.45}{30.2} = 18.1$ per cent. If the manufacturers of ordinary elevators would multiply the net work done by the elevator by five or six instead of two, they would come closer to the actual torque required to start the load with a new hoisting equipment.

So far only starting efficiency has been considered, for experience has clearly shown that once the load is started a much smaller amount of torque is required to lift it. The reason for the greater torque required to start the load over that required to lift it is probably due to the fact that there is an opportunity for the load to squeeze the oil from between the worm and worm wheel and from the bearing that carries the end thrust of the worm, so that at the instant of starting the surfaces are dry and the metallic surfaces are in direct contact with each other, while after starting, oil is carried between the surfaces and during the lift the metallic surfaces have a film of oil between them, thus greatly lessening the friction.

In order to obtain an intelligent conception of the best type of motor for operating motors and hoists, it will be necessary to know approximately the character of the load. We know that the starting torque is higher than the running torque. The question is, how much higher? Inquiry among the manufacturers of gears and elevators and worm drive automobiles failed to give an answer to the question and it was decided to answer it by direct experiment on a freight elevator.

The elevator selected has been in use for two and a half years and has a full load capacity of 3000 lb. It has a steel worm and cast iron gear, the worm being entirely under oil. The starting torque was found by loading the car with 3000 lb. and following the method shown in Fig. 1. The running torque was found by carefully measuring the input in watts and deducting the watts lost in the stator windings and stator iron. The difference was, of course, delivered to the rotor, which, taken in connection with the synchronous speed, determined the torque. The net torque, after deducting the weight of that part of the wrench handle carried by the spring balance, was 45 lb. and the radius 3 ft. 9 in. The corresponding torque at one ft. radius is then $45 \times 3.75 = 169$ lb. The power supplied to the motor in order to lift the load showed a variation of at least 40 per cent, a little over 10 kw. being required to lift the load on some of the up trips and over 14 kw. being required on other trips with the same load. Let us take 12 kw. as the average power input. The I^2R loss in the stator coils and the iron loss in the stator iron equals at this current approximately 1800 watts. There will be, therefore, 10.2 kw. or 13.7 h.p. delivered to the rotor. The torque at one ft. radius corresponding to 13.7 h.p. equals 80 lb. The running torque is, therefore, about one-half of the starting torque on this particular hoisting equipment which had been in use two and a half years.

The gear ratio and drum diameter on this machine were such that at synchronous speed of 900 rev. per min. the load would be lifted at 70 ft. per minute. The counterbalance was a little short, so that the net load lifted when 3000 lb. was put on the elevator was about 2100 lb. The useful work done then was $\frac{2100 \times 70}{33{,}000} = 4.45$ h.p. The power delivered to the rotor was 13.7 h.p. The running efficiency is therefore $\frac{4.45}{13.7} =$ 32.5 per cent, and the starting efficiency about half of this, or about 16 per cent. I believe both the starting and running efficiency of this machine are low on account of the cast iron gear, and that the starting efficiency of this machine after two and a half years of use is about what is obtained by a hoisting equipment with a new bronze gear.

The voltage drop in any a-c. circuit is due to two factors, first, the drop due to ohmic resistance, depending on the amount of current and the resistance of the transformer and connecting wires. The other source of drop is due to the inductance of the transformer and leads. In this paper it will be assumed that the drop in the leads and in the primary supply is equal to the drop in the transformer. A company manufacturing a standard line of three-phase transformers has given me the following figures:

(The figures given are the sums of the *IR* drops and inductance drops given as percentages of the applied voltage.)

	Power Factor				
	60%	70%	80%	90%	100%
5 kw.	2.3%	2.4%	2.3%	2.2%	1.7 %
7.5 "	2.1 "	2.2 "	2.1 "	2.0 "	1.55 "
10 "	2.2 "	2.2 "	2.1 "	2.0 "	1.45 "
15 "	2.5 "	2.5 "	2.4 "	2.1 "	1.35 "
20 "	2.6 "	2.6 "	2.4 "	2.2 "	1.35 "

It will be seen from this table that in transformers of 15 kw. and above, the drop at 70 per cent power factor is nearly twice what it is at 100 per cent. At 71 per cent power factor, the real watts and the quadrature watts are equal. It is clear from this table that the drops are proportional to the current, and further, the drops increase as the power factor decreases.

It will be necessary then to examine the characteristics of wound-rotor motors and the special squirrel cage motors referred to in this paper to determine the currents required to give the required torque and the power factor of the currents.

By what is known as a Heyland circle diagram it is possible to show graphically the current required by an induction motor to produce a given torque, the maximum torque the motor is capable of producing and the power factor under the different conditions.

Fig. 2 is the circle diagram of a slip-ring motor, in which *oy* is the vertical axis, and quantities parallel to this axis may be read as true watts, or as torque, when multiplied by the proper constant; *ox* is the horizontal axis and quantities parallel to this axis may be read as quadrature watts; *oa* represents in length the current taken by the motor running light. The angle *yoa* is the angle of lag of the current behind the voltage, and *od* shows the current that will be taken when the short-circuited rotor is blocked or cannot revolve. The current that would be taken if there were no ohmic resistance in the rotor is represented by *oc*. The length of the line *df* represents the torque delivered by the motor when all resistance is cut out of the rotor circuit, or when the rotor is short-circuited. If resistance equal to nearly twice the resistance of the rotor is inserted into the rotor circuit, the current taken by the motor when blocked is reduced to *oc* but the torque is increased to *cg*. If the resistance in the rotor circuit is increased to about 6.5 times that of the rotor, the current taken by the motor is decreased to *ob* and the torque changed to *bj*.

Ideal Theoretical Operation of Wound-Rotor Motors

In theoretical ideal operation, a high resistance is inserted in the rotor circuit and the primary current would be represented by *ob* at the instant the current is thrown on. The motor is supposed to start and if it does, the increase in speed of the rotor acts like an increase in the resistance in the rotor circuit, so far as the primary current is concerned, and the primary current decreases as the rotor speed increases. The slip is very large on account of the large external secondary resistance and after the rotor has attained a proper speed, part of this resistance is cut out and the total resistance is reduced from 6.5 times to about twice the resistance of the rotor. Reducing the resistance of the rotor circuit reduces the slip in the rotor, and the speed is therefore raised. Cutting out this resistance increases the current in the primary, but the speed of the rotor is supposed to be high enough when the resistance is cut out so that the primary current does not rise above *ob*.

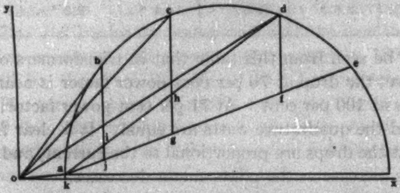

Fig. 2

After a further increase in speed, the remaining resistance of the rotor is cut out and the rotor runs at nearly synchronous speed to the end of the trip. It will be noticed that the torque per ampere in the starting condition corresponding to *ob* is high, the torque corresponding to the length of the line *bj* and the primary current to *ob*. Further, the power factor of this current is good, the angle *box* being large, and therefore its cosine is small. It is upon the supposition that slip-ring motors operate in the manner just described that they are preferred or required by many power companies.

THE ACTUAL OPERATING CONDITIONS

Let us examine the actual operating conditions. A majority of elevator controllers are of the series relay type and are so designed that the second step of resistance will not be cut out until the motor starts, and the line current, therefore, is reduced by the rotation of rotor to less than a predetermined maximum. The reason for this is to secure the ideal cycle described above. Unfortunately, the motor may have to lift its maximum load at times, and therefore, the resistance must be so adjusted that the motor will *be sure to start.* Therefore, instead of the first step having a high rotor resistance and a small primary current corresponding to *ob,* Fig. 2, the resistance must be adjusted at a much smaller value so as to give the primary current shown in Fig. 2, or *oc,* in order to give the maximum starting torque *cg.*

If the torque required to start the elevator is nearly equal to the maximum torque the motor will deliver, it will be necessary to adjust the secondary resistance to get the maximum torque, and therefore the primary current shown in Fig. 2 by *oc.* The torque per ampere with the primary current *ob* is 30 per cent higher than with the current *oc.* Further, it is likely that in adjusting the secondary resistance to give the maximum starting torque this resistance may be too low. If such an adjustment was made for the motor shown in Fig. 2, the current at starting might be increased from *oc* to *od* but the torque would be decreased from *cg* to *df.* The torque per ampere, as compared with the secondary resistance adjustment that gave the primary current *ob,* would be only a little over one-third. Further, the current *od* has a lower power factor than the current *oc* and only about half the power factor of the current *ob.* From the standpoint of the central station man, it is the possibility of bad adjustment when the controller is new and the probability of bad adjustment when the controller is old and worn, that constitute the great objection to the wound-rotor motor.

A SQUIRREL CAGE MOTOR DESIGNED ESPECIALLY FOR ELEVATOR AND HOIST DUTY

The above considerations induced the writer to design, several years ago, a special squirrel cage motor for elevator duty. This motor has a rotor of very high resistance, and therefore the maximum or starting current is only one-third to one-half of what it would be with the ordinary squirrel cage motor. The torque at starting is about 85 or 90 per cent of the maximum torque the motor could deliver with a rotor having such a resistance as to give the maximum torque. The characteristics of such a motor are shown in the larger circle in Fig. 3. The smaller circle in the same figure shows the characteristics of a wound-rotor motor with the same stator winding and the same number of slots in both stator and rotor. The line *bj* shows the maximum torque of 610 ft-lb. that could be obtained from the motor by a primary current *ob*. The line *ac* shows the actual torque that is obtained by the use of an extra high resistance rotor. The torque corresponding to primary current *oa* is *ac*, or 540 ft-lb. This is 88 per cent of the maximum obtainable torque. The torque per ampere with the primary current *oa* is, however, about 30 per cent higher than it would be if a rotor of lower resistance were used and a primary current *ob* was obtained. With a motor of this construction it is impossible to obtain large currents at low power factors such as would result from an improper adjustment of resistance, or defect in the controller of the wound-rotor motor. The torque per ampere and the power factor at maximum current are always high. It will be seen that the maximum torque that can be obtained from this motor supplied with a wound rotor is 470 ft-lb. This would be obtained with a current *ok* which is greater than *oa*, and also of lower power factor. If a maximum torque of say 500 lb. was required it would

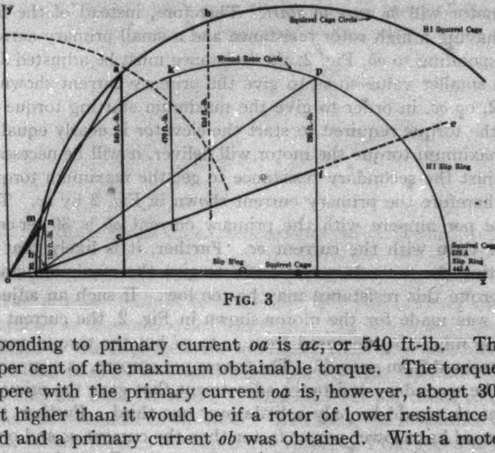

FIG. 3

not be possible to use a wound-rotor motor built with this size of frame and a larger frame would have to be used. In Fig. 4, the larger circle is a duplicate of the large circle of Fig. 3 and shows the characteristics of a squirrel cage motor with a special rotor. This frame is designed for a 15-h.p. squirrel cage motor for continuous duty with a 35 deg. temperature rise. The smaller circle shows the characteristics of a wound-rotor motor of the next larger frame, rated at 20 h.p., for continuous duty at 35 deg. temperature rise. It will be seen that the maximum torque of the wound-rotor motor is practically the same as that of the squirrel cage; 625 and 610 ft-lb. repectively. Let us see how the two motors compare at the maximum torque of the squirrel cage motor, 540 ft-lb. The line *oa* represents the primary current of the squirrel cage motor, and *ob* the primary current of the wound-rotor motor required to produce the same torque of 540 ft-lb. The current *ob* is a little greater than *oa* and has a little poorer power factor.

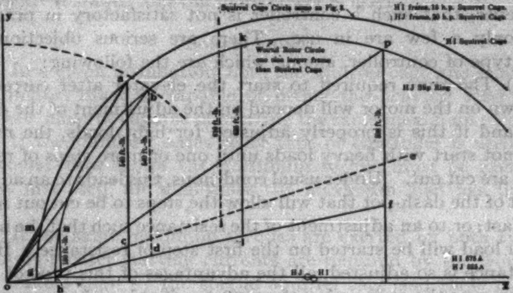
Squirrel Cage Circle same as Fig. 3.
HI frame, 15 h.p. Squirrel Cage
HJ frame, 20 h.p. Squirrel Cage
HI Squirrel Cage
Wound Rotor Circle one size larger frame than Squirrel Cage
HJ Slip Ring
y
k
p
a
b
e
f
m
n
c
d
g
o
h
x
HJ
HI

FIG. 4

To compare the two motors at light load, I have assumed that 150 ft-lb. was the torque required of the motor to lift the ordinary load on the elevator after starting. Line *om* shows the primary current required by the squirrel cage motor and *on* the current required by the wound-rotor motor. At ordinary loads, then, the wound-rotor motor takes more current and this current has a lower power factor.

Our examination, therefore, has shown that the special squirrel cage motor is superior to the wound-rotor motor when both motors are required to produce the same maximum torque.

It is also superior when both motors are running at light loads. Let us consider, then, if there are any circumstances under which the wound-rotor motor would be superior to the special squirrel cage motor.

If instead of using the standard series relay type of controller for the wound-rotor motor, a dash-pot type of controller were used, it is clear that if the load on the elevator and the required starting torque were small, the wound-rotor motor would start up with such a high resistance in the secondary circuit as to give a small primary current and much less than the maximum torque. Such an installation would start a light load with less primary maximum current than the special squirrel cage motor, and if a greater torque was required, it could be obtained when the second step of resistance was cut out. Experience seems to show, however, that such a controller is not satisfactory in practise, for only a few are in use. There are serious objections to this type of controller, among which are the following:

(a) The time required to start the elevator after current is thrown on the motor will depend on the adjustment of the dash-pot and if this is properly adjusted for light loads, the motor will not start with heavy loads until one or more steps of resistance are cut out. Under usual conditions, this leads to an adjustment of the dash-pot that will allow the steps to be cut out much too fast, or to an adjustment of the resistance such that the maximum load will be started on the first step of resistance. If the resistance is so adjusted, all the advantages of this type of controller over the series relay type are sacrificed, and any possible advantage of the wound-rotor motor over the special squirrel cage motor is also sacrificed.

(b) The adjustment of a dash-pot will not remain constant. Changes in the temperature of the dash-pot will affect the adjustment, and the presence of dirt and corrosion will also affect it. These causes may be depended upon in time to so alter the time of operation of the controller that a change in the adjustment of the controller will have to be made. The great danger in such a change is that it will allow too rapid a movment of the controller. Such a rapid movement with light load on the elevator will not affect operation, but if the maximum load is put on the elevator it is likely that the motor will pass through its position of maximum torque (see Fig. 2) before the motor has attained much speed, and reach the condition represented by the primary current of Fig. 2, in which the torque is only about half the maximum, and in consequence the elevator would stall. This is the difficulty that the series relay type of controller eliminates.

A secondary advantage of the special squirrel cage motor from the standpoint of the central station man is its more satisfactory service as compared with the wound-rotor motor and its controller. Experience has shown that nearly all the delays and troubles on wound-rotor motors are due to small repairs and adjustments on the controller, slip rings, brush holders and brushes. If the special squirrel cage motor is used, the controller slip rings, brush holders, brushes and wound rotor are eliminated; therefore, the service is less liable to interruption. It is to the interest of the electric power station to have devices on its line that give no trouble; for the less trouble experienced, the more motors are installed and the more power is used.

CONCLUSIONS

(1) In a given installation, both the squirrel cage and wound-rotor motors must be capable of lifting the heaviest load and therefore must be capable of exerting the same maximum torque.

(2) If the standard series relay type of controller is used on the wound-rotor motor the maximum torque must be exerted on the first step, for sometimes the maximum load has to be lifted.

(3) If the same maximum torques are exerted by both types of motors greater starting currents are required by the wound-rotor motors than by the special squirrel cage and these larger currents are taken from the supply lines at lower power factors.

(4) In lifting the ordinary load, which is much less than the maximum, more current is required by the wound-rotor motor, and this current is taken from the lines at lower power factor.

(5) In order that the wound-rotor motor may start with less current than the special squirrel cage motor, under any circumstances, a controller must be provided in which the steps of resistance are cut out in approximately equal time intervals. This is best accomplished by means of a dash-pot. Experience has shown the dash-pot controller to be subject to so many troubles that few of them are used.

(6) Elimination of the first cost, maintenance and troubles of controller and slip-ring motors, by the use of special squirrel cage motors will cause more motors to be installed on low-speed elevators and hoists, and more current to be sold.

DISCUSSION ON "LINE DISTURBANCE CAUSED BY SPECIAL SQUIRREL CAGE AND WOUND-ROTOR MOTORS WHEN STARTING ELEVATORS AND HOISTS" (LINCOLN), CLEVELAND, OHIO, MARCH 18, 1915.

H. D. James: I was connected for five years with a large elevator company and wish to state that this company had very good information on the efficiency of its machines. This was based on several hundred tests showing the torque required to start the elevator and the power required to operate it. Undoubtedly Mr. Lincoln is referring to smaller companies that have not accumulated much of this information. Mr. Lincoln states in his conclusions—"If the standard series relay type of controller is used on the wound-rotor motor the maximum torque must be exerted on the first step, for sometimes the maximum load has to be lifted." The torque referred to is the torque at the circumference of the hoisting drum and the amount of torque exerted by the motor will depend upon the gear ratio between the motor and the drum. An elevator is sold to lift a specified number of pounds at a specified speed. Let us assume that the load is 3000 lb. and it is to be lifted at the rate of 100 ft. per min. The motor must be geared to the drum to give this speed of car with the load specified. In selecting the gearing the synchronous speed of the motor can not be used, as an induction motor runs at a speed less than synchronism, depending upon its full load slip. If we assume that a cage motor is used having 30 per cent full load slip and compare it with a slip ring motor having 4 per cent slip, it is readily seen that there is a gear ratio in favor of the slip ring motor of approximately 40 per cent. The slip ring motor will be required to exert 40 per cent less torque than the squirrel cage motor to start the same load. The current taken in starting on the first notch of the controller is the current corresponding to the torque required to start this load. It is not the current corresponding to the same torque at the motor shaft. Mr. Lincoln points out that the squirrel cage motor can be designed to exert a given torque with less amperes input than the slip ring motor. This is true as the squirrel cage motor has a better interlinking of induction between the primary and secondary than the slip ring motor. This comparison, however, is not a true one. It has been shown above that the slip ring motor runs at a higher speed than the squirrel cage motor and, therefore, has a different gear ratio which favors the slip ring motor at starting. In order to compare the two motors the torque required to start a given load should be determined for each type of motor and the current input at this torque compared. An analysis of this kind will show that the secondary resistance of a squirrel cage motor can be increased with profit up to a certain point, beyond which the advantages of increased resistance are more than counterbalanced by the increased slip of the motor. The gear ratio to give full speed will increase the torque required from the motor faster than the resistance will improve this torque. Where the slip ring motor and the squirrel cage motor are both proportioned to give the best results when referred to the speed of the car, it will be found that the amperes input to start the load will not differ materially in the two designs.

The slip or speed regulation of the motor bears another important relation to the elevator. The motor is sometimes driven as a generator in lowering loads. This causes the motor to run above synchronism at a speed determined by the slip of the motor. If this slip is great the difference between the speed lifting the load and the speed of lowering the load will be so great that it will be difficult to stop the elevator safely under the latter conditions. As an example, a motor with 30 per cent slip is geared to an elevator giving a hoisting speed of 100 ft. per min. under full load. In lowering this load the speed would be approximately 175 ft. per min. If the slip of the motor were reduced to 15 per cent instead of 30 per cent the load would be lowered at about 130 ft. per minute. The difference between the hoisting and lowering speeds, while considerable, is not important with low-speed elevators. It becomes of increasing importance, however, with an increase in the car speed. The modern high-speed traction elevator demands such close speed regulation that this alone determines the size of the motor. The above will be very apparent when we consider that the car must be stopped automatically at either limit of travel and that the energy dissipated in stopping the car is proportional to the square of the car speed. The amount of over-travel beyond the terminal landings is quite limited, so that safety requires close speed regulation on high-speed elevators.

The advantages to be obtained by the use of a squirrel cage induction motor were first pointed out by Mr. B. G. Lamme in a paper he read before the National Electric Light convention in 1897. As early as 1900 many of these high-resistance squirrel cage motors were being used for elevator service in New York City. They gave excellent results when properly applied.

Both the squirrel cage motor and the wound-rotor motor have their proper place in elevator service. Mr. Lincoln has brought out the advantages of the squirrel cage motor. Where this motor is limited to low-speed elevator work, the absence of all complication in the controlling device and the simplicity of the motor itself are the controlling factors. Efficiency and speed regulation are usually of less importance. For higher speed work the slip ring motor gives as good a starting condition with better regulation; it has a more complicated controller and requires better attention. I am heartily in favor of any motor that reduces the peak demand on the power service, but the reason for using a motor is to render service to the customer, and we must not sacrifice the starting characteristics to the detriment of the service obtained.

R. H. McLain: On the subject of the possibilities of this squirrel cage motor for elevator work, I think that the purpose a power company tries to perform is to give service to its customers and make it possible for the customers to use electricity in a profitable manner. To do this it certainly should not make any rules that would arbitrarily rule out a particular kind of motor merely because it is called a squirrel cage motor or a wound-rotor motor; but should take into account the things which have been pointed out in the characteristics of the two motors. I fully agree with Mr. James in what he has said of the wound-rotor motor and I fully agree with Mr. Lincoln on what he has said about the squirrel cage motor. I really do not think they conflict. I think Mr. James carried the discussion further than Mr. Lincoln had carried it, and in my mind it comes to this: A squirrel cage motor has a proper field for application where you want a low-speed elevator, where your power system is large and where high currents do not actually affect the line voltage. The object of a good many rules, I think, is to discourage the tendency to use these motors rather than to prevent actual voltage disturbances taking place. The field for the slip ring motor is undoubtedly on higher speed work or in places where it is worth considerable money to a power company to prevent occasional flickerings of the lights. This latter would only apply to very small power companies.

H. L. Wallau: From the point of view of the power company I think there is one thing to be borne in mind, and that is, that with either type of motor having a given impedance Z and starting from standstill, a current I equal to E/Z is taken; but the duration of this starting current has a very appreciable bearing on the situation. Therefore, a high torque per ampere, which means that the motor is going to accelerate quickly and reduce the starting current rapidly, is really to be striven for.

R. H. McLain: One word right in line with that. Where the squirrel cage motor is properly used on low-speed work and constructed as has been mentioned, that motor will have a lower flywheel effect than the slip ring motor, which is bound to be larger. Therefore, the power peak which it takes will last for a shorter time than the peak of the slip ring motor. I think that point should be considered in favor of the squirrel cage motor.

J. C. Lincoln: This paper was written from the standpoint of motors requiring not over fifteen or twenty horse power, for small freight work and small hoist work. I will agree with Mr. James heartily that when you get into other work, where efficiency comes into play, the high-resistance squirrel cage motors I have described are not the best thing that can be used; but in sizes up to fifteen or twenty horse power I think that Mr. James will agree with me that the best type of motor is the one that I have described.

I would like to call attention to this: That, given the same maximum torque required in the small motors up to twenty horse power, we will see that the torque per ampere, from the nature of the case, is higher in the squirrel cage motor than it is in the corresponding wound-rotor motor. Therefore, from the standpoint of the central station man, assuming that the motor has got to lift its maximum torque, the squirrel cage motor will produce a little less disturbance than the wound-rotor motor which will give the same torque

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SOME TROUBLES ENCOUNTERED IN THE OPERATION OF CARBON BRUSHES IN DIRECT-CURRENT GENERATORS AND MOTORS

BY E. H. MARTINDALE

ABSTRACT OF PAPER

This paper deals very briefly with troubles which affect the operation of carbon brushes on motors and generators. It should be of great assistance to the operator in locating various machine troubles and in securing the best service from his brushes. The paper is divided into five sections, based on the location of the cause of trouble: (1) field, (2) armature, (3) commutator, including brush rigging, (4) external electrical, and (5) external mechanical.

IT IS the purpose of this paper so to discuss the causes and effects of troubles encountered in the operation of motors and generators that the operator will be better able to use his brushes to the best advantage.

The characteristics of carbon brushes which most commonly affect the operation are resistance, hardness, abrasiveness, coefficient of friction, contact voltage drop and heat conductivity. None of these terms needs explanation, but the writer wishes to emphasize the importance of not confusing hardness with abrasiveness. By abrasiveness we mean the scouring or cutting action of the brush. Hardness of carbon brushes can best be determined by the use of a scleroscope, an instrument used to determine the hardness of steel and other metals. Relative hardness may be judged by cutting the brush with a pocket knife or by marking with it on paper, or if more accuracy is desired by the layman, a set of pencils from 2 B to 8 H will be a great aid, as a pencil softer than the brush will mark it and one harder will scratch it. The hardest brush with which the writer is familiar has no abrasive action, while one of the softest brushes has a decided abrasive action.

In this paper the brush troubles will be divided into five classes depending on the location of the cause of trouble, (1) field, (2) armature, (3) commutator, including brush rigging, (4) external electrical, and (5) external mechanical.

FIELD TROUBLES

As the field coils are connected in series or series-parallel, a partial short circuit may occur in one coil without materially affecting the heating of the coil. This will usually be attended with severe sparking at one or two studs, although in a wave-wound machine the commutation may be very little affected. This trouble can best be located by the voltage drop across each coil, with a constant current through the coils. Similar trouble may be caused by an error in rewinding a field coil. On some machines the shunt fields are connected with two or three fields in series and two or more of these groups in parallel. A partial short circuit in one coil will then affect the entire group, electrically unbalance the machine, and cause heavy short-circuit currents.

In a cumulative compound machine one series field may be reversed accidentally, with the result that as the load increases sparking will occur usually at the two adjacent studs; or the entire series fields by mistake may be connected to oppose the shunt field, which will result in blackening of the commutator, and severe sparking under heavy loads. The best way to detect this trouble is to excite separately the shunt field and the series field, being sure that the current flows in the same direction as when the machine is in operation. The polarity of each pole should be tested with a compass and should reverse as the compass is passed from one pole to the next. Further, the polarity of each pole should be the same when either field is excited. In a generator the voltage will decrease and in a motor the speed will increase as the load increases.

Unequal air gaps are responsible for a great deal of commutation trouble. If one pole face is nearer the armature the flux across the gap is greater and a higher voltage will be developed in the coils under that pole. This may result in very heavy short-circuit currents between the studs adjacent to that pole and other studs of the same polarity. Fig. 1 shows such a condition due to worn bearings which allow the armature to run nearer the lower pole pieces. In machines with cast frames, blow holes may be present, and may be large enough greatly to increase the reluctance of the magnetic circuit and cause a lower voltage to be developed in one section of the armature with resultant short-circuit currents.

ARMATURE

An open circuit in an armature coil causes the most vicious form of sparking, which is always accompanied by severe pitting of the mica between the commutator bars connected to this coil and the adjacent coil. The usual method is to connect an incandescent lamp in a circuit, and with two pointed terminals make a bar to bar test on the commutator; the open circuit is shown when the lamp does not light. Similar sparking in a less degree may be caused by a high-resistance connection between the end of a coil and the commutator riser. This can be detected by passing a current through the armature and taking voltage drop between adjacent bars, as the voltage will be higher than normal when the poor connection is in the circuit measured. This method may also be used to detect an open circuit, but a voltmeter reading as high as the voltage impressed on the armature must be used, as full voltage will be obtained across the open circuit.

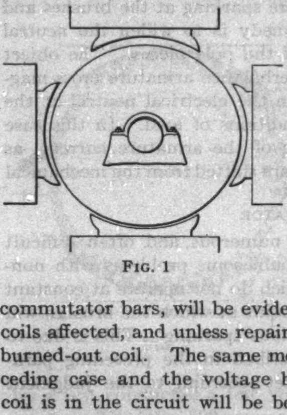

FIG. 1

A short circuit between two sections of a coil, two coils in the same slot, end connections of two coils, or between the commutator bars, will be evidenced by excessive heating of the coils affected, and unless repaired will sooner or later result in a burned-out coil. The same method may be used as in the preceding case and the voltage between adjacent bars when the coil is in the circuit will be below normal.

The demagnetizing and cross-magnetizing actions of an armature have serious effects on the commutation of many machines. To get good commutation in a non-interpole machine, the brushes usually must be set ahead of the mechanical neutral on a generator and back of the mechanical neutral on a motor. Fig. 2 shows a sketch of a generator in which the brushes have been shifted ahead of the mechanical neutral 10 deg. The section between a and b and a' and b' acts as an electromagnet with poles at N'' and S'' opposing the field magnetization. This is the demagnetizing action. The section $b\ a'$ and $a\ b'$ acts as an electromagnet with poles at N' and S'. This is the cross-magnetizing action of the armature and it tends to increase the magnetism of the right-hand side of *N* pole of Fig. 2 and the left-hand side of *S* pole, and tends to decrease the magnetism of the left-hand side of *N* pole and the right-hand side of *S* pole.

If the brushes are shifted far to obtain good commutation, and if, at the same time, the magnetization of the pole piece is not well above the knee of the saturation curve, the demagnetizing effect of the armature may seriously reduce the voltage of a generator or increase the speed of a motor. On the other hand, the cross-magnetizing effect may be sufficient, if the brushes are not shifted to the electrical neutral, to place the coils undergoing commutation in a heavy field, with resultant heavy short-circuit currents, severe sparking at the brushes and all the attendant evils. The remedy is to widen the neutral field by filing away the edges of the pole pieces. The object of interpole windings is to counterbalance armature cross-magnetizing action and thus maintain the electrical neutral at the mechanical neutral under all conditions of load. In this case there is no demagnetizing action of the armature current, as this occurs only when the brushes are shifted from the mechanical neutral.

COMMUTATOR

Commutator brush troubles are numerous, and often difficult to identify. One of the most troublesome problems with non-interpole generators or motors which do not operate at constant load is the difficulty of finding a point at which the brushes will operate at all loads without injurious sparking. This is due to the cross-magnetizing action described in the preceding paragraph. The brushes are usually set according to the judgment of the operator.

Spring tension or the pressure with which the brushes bear on the commutator seldom receives proper attention except in large central stations or mills and even there it is often neglected. The most economical pressure is the lowest consistent with a low contact loss, a clean commutator and freedom from sparking, glowing or pitting of the brushes. It is seldom advisable to use a pressure less than 1½ pounds per square inch of cross-section. The writer recommends on stationary machines a pressure of from two to four pounds per square inch, depending on local conditions and the grade of brush. He recommends from four to eight pounds per square inch for crane motors, haulage motors, railway motors and similar machines. On stationary motors he has found pressure as low as one quarter pound per square inch and as high as fifteen pounds per square inch.

Brush spacing is very important, but usually neglected. In Fig. 3 the studs are equally spaced and the dotted lines show the correct brush position, but due to the brush holders on arm *A* being rotated too far in one direction and on arm *C* too far in the opposite direction the voltage generated in section *A B C* is different from that in *A F E* or *C D E* and this will result in shortcircuit currents between *A*, *E* and *C*, high enough to neutralize the unequal voltage.

The magnitude of this short-circuit current may be illustrated by a test conducted a few years ago by the writer on the 400-ampere, 250-volt, 600-rev. per min., six-pole shunt generator shown in Fig. 4. On one positive stud which we will call *A* the brush holders were rotated to place the brush ¾ in. ahead of correct position. The other positive studs *B* and *C* were left unchanged. The busbar had been calibrated with a millivoltmeter to determine the current flowing. With the brushes incorrectly spaced but operating at the best point, the short-circuit current was not excessive. When the brushes were shifted two bars away from the neutral and with no external load on the machine the short-circuit current rose to 800 amperes or twice the normal full load current of the generator. As the voltage back of this current was low the actual power loss was

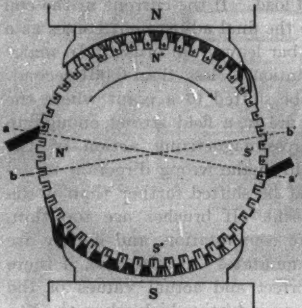

FIG. 2

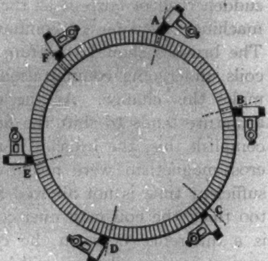

FIG. 3

small, but the heating of the windings and the effect on commutator and brushes was serious. The current density in the brushes on stud *A* was over 200 amperes per square inch and on studs *B* and *C* over 100 amperes per square inch. This is an extreme case, but a smaller difference in spacing may often be serious. Spacing may be checked by counting the number of bars between each pair of studs but a better way is to cut a strip of paper the length of the commutator circumference, mark off equal divisions corresponding to the number of studs, place the paper on the commutator and make the brushes toe the mark.

From the time a commutator bar touches one edge of a brush until it leaves the opposite edge, the current in the coil undergoing commutation should fall from full load to zero and rise in the opposite direction to full load. If the current in the coil is more or less than that value the final adjustment comes as a sudden rush of current as the bar leaves the brush. In many machines the time of commutation is less than 0.001 second. The brushes should therefore be shifted to a point where the coils undergoing commutation are in a field strong enough to make this change. As the cross-magnetizing action of the armature tends to shift the field in the wrong direction to accomplish this, the brushes must be shifted farther than if the cross-magnetism were not present. If brushes are too thin, sufficient time is not allowed for commutation, and if they are too thick the coil may over-commutate. In any case, if there is a difference between the correct and actual values of the current in the coil there will be an inductive kick when the bar leaves the brush. If the inductance of the coil is high or the difference in current great, more or less severe sparking may result. Many cases of sparking have been cured by reducing the thickness of the brush.

A similar condition sometimes arises when the brush studs or brush holders are not parallel to the commutator bars, the short-circuit current in this case passing from one brush through the stud to another brush and thence through the coil. Such trouble is often found on some old machines still in service, on which the brush holders and brushes change position as the brushes wear away.

If there is not sufficient clearance between a brush and its holder or if foreign matter becomes lodged in the holder the brush will not move freely and may make poor contact and result in blackening of commutator, sparking, heating and other evils.

PLATE XXXVI.
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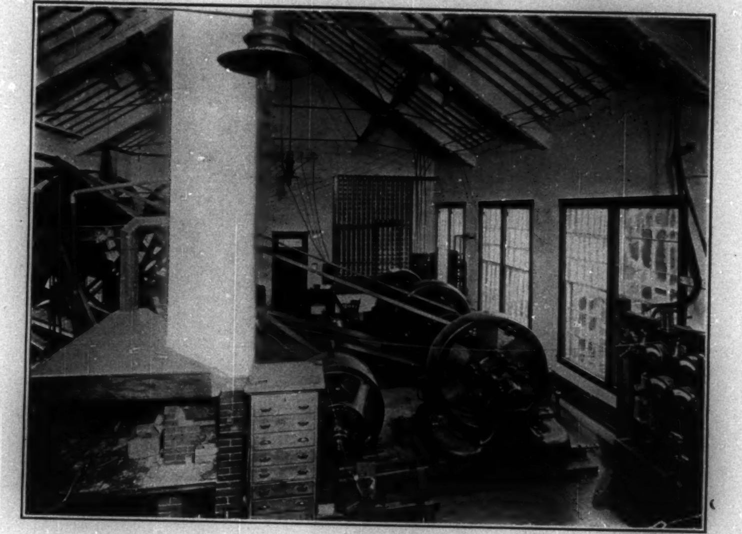

FIG. 4

[MARTINDALE]

On the other hand if there is too much clearance and the brushes are not equipped with shunts the current may pass from the brush to the brush holder through a small arc and cause undue wear of the holders. On machines which have been in service a long time much trouble frequently arises from worn holders. This is particularly true if the machine runs in both directions, as the brush face changes when the machine is reversed and thereby reduces the time of commutation and increases the current density in the brush faces. Brushes in worn holders are also more inclined to chatter and chip.

There are many types of brush shunts or pigtails on the market; some have a relatively high resistance when manufactured, while others become loose due to heating or vibration and cause a large proportion of the current to pass from the brush directly to the holder. A poor connection between the terminal and the stud may have the same effect.

Sometimes the hammer which bears on the brush becomes bent and does not bear evenly or radially on the brush. This may cause such a side push or twist that the brush will not move freely in the holder, and may cause sparking, burning and the attendant evils.

Brushes are sometimes ordered longer than standard with a view to securing a longer life, but the spring will usually give a side push and cause trouble, which will shorten the life of the brushes and perhaps damage the commutator.

Noise of carbon brushes is due to a mechanical vibration called chattering. If due to the friction of the brush on the commutator the noise may have various pitches. The remedy is a change in spring tension, angle of operation or grade of brush, although relief may be obtained by lubrication of the commutator at intervals. If the noise is due to high mica or wide slots in a slotted commutator the pitch of the sound will correspond to the number of bars passing under the brush per second. If the trouble is high mica the remedy is the removal of the cause of the high mica, or the use of a more abrasive brush, or undercutting the mica. If the noise is caused by slots it may be necessary to change the spring tension, angle of operation, or grade of brush, as lubrication is not advisable on a slotted commutator.

The causes of short-circuit currents have been mentioned under other heads in this paper and are, briefly: operation of brushes at wrong commutation point, incorrect brush spacing, brushes spanning too many bars, brushes not parallel with commutator bars, field trouble, including unequal air gaps, and to these might be added brushes with too low contact drop. Short-circuit currents represent a low power loss but are serious in their effects on operation. They may produce excessive heating, sparking, high mica, blackening of commutator, burning away of commutator, flat spots, pitting or honeycombing of brush faces, picking up copper by brushes and short life of brushes. The remedy is to find and remove the cause, not always an easy thing to do.

As the expression "short-circuit currents" is not entirely distinctive, the writer would like to see some other phrase adopted as standard, such as "trouble currents." This name would be well suited, as they never do any good and always do some harm, if no more than wasting energy by unnecessary heating.

Pitting or honeycombing of brush faces is nearly always caused by short-circuit currents or a very low brush pressure but occasionally it is due to insufficient carrying capacity of the brushes. It can generally be determined from the appearance of the brush face whether the pitting is caused by low pressure or short-circuit currents; in 95 per cent of the cases it is the latter. Many cases of pitting may be corrected by reducing the thickness of the brushes, but it is better practise to look for some other cause first, as already described.

The writer has never been satisfied with any explanation he has seen for "picking up copper", which term is applied when particles of copper from the commutator become embedded in the brush faces. It is generally attributed to an electrolytic action, and it is a fact that when the trouble appears it is nearly always on the positive brush of a generator, the negative brush of a motor or a brush which shows heavy short-circuit current. This bears out the theory that the copper is carried by the current and deposited on the brush. On the other hand, the writer has seen a brush pick up copper when running under test on a copper slip ring without any current flowing. This purely mechanical action was attributed to abrasive material in the brush which tore off the copper particles. As the abrasive particle no doubt reaches a high temperature a small copper particle may become welded to it and other particles collect on this until the abrasive spot is itself worn away. Picking up copper lowers the contact resistance between brush and commutator and generally causes heavy short-circuit currents.

A loose commutator bar may be flush with other bars when the machine is stationary but may be thrown out slightly when running, due to centrifugal force. This will lift the brush, and will burn one or more bars just ahead of the high bar, depending on the number which the brush spans, and further, will burn some of the bars back of the high bar, depending largely on the speed of the machine and the brush pressure. Its presence can often be detected by the knocking sound of the bar hitting a brush once every revolution.

Commutator bolts should be tightened a few months after the machine has been placed in service. The writer knows of one case where high bars appeared to be causing trouble, and the commutator bolts were tightened, but to no avail. The machine was then dismantled and it was found that the V-ring reached its seat before clamping the commutator bars tightly.

In repairing commutators and sometimes in manufacturing them, commutator bars of different hardness are used and one bar may wear faster than another, causing a flat spot or a high bar.

Necessarily, many of the troubles overlap, and some causes for high mica have been given previously in this paper. They are, mainly, some form of sparking which burns away the commutator bars, leaving the mica to project. If the cause cannot be located and removed it is necessary to undercut the mica or use a more abrasive brush. The former is preferable, as the life of the commutator and brushes will be longer. When the mica once becomes high it holds the brush from the bars, causes more burning, and the commutator rapidly becomes worse.

Blackening of a commutator may be caused by sparking, the use of too much lubricant or by the character of the brush. Blackening will sometimes occur on every other bar or every third bar, corresponding to the number of coils per slot, and may often be shifted to another set of bars by shifting the location of the brushes. This seems to be due to a magnetic kick in the coil undergoing commutation when the armature tooth next to the coil suddenly leaves the field. The remedy is to have the neutral field wide enough to permit the tooth to leave the strong field before the commutator bar comes under the brush.

Flat spots consist of a few bars between which the mica is high. They may be started by the commutator not running true, soft bars, difference in hardness of mica, surges of current or any sparking which occurs once every revolution. When a flat spot starts it may soon develop other flat spots, equidistant about the commutator, one for every pair of poles. This is probably explained by the fact that when the flat spot reaches a brush the current through that brush is greatly reduced. This throws the extra load on the other studs of the same polarity and may produce a spark at each of the studs. Unless given prompt attention the spots may gradually spread until high mica is present over the entire commutator. The cause for the flat spots should be located and removed if possible. An interesting case was recently called to the writer's attention by Mr. A. M. Lloyd. A 200-h.p., 250-volt, six-pole motor with 30 brushes had for some time persisted in developing flat spots. The commutator was carefully cleaned and on one section brushes were installed on only two studs. In a few days flat spots had developed on all of the commutator, except that section; two more brushes were added and still no flat spots on the section; the other two were added and the flat spots developed in a short time. One brush was removed, the commutator cleaned and no flat spots developed in this section. This narrowed the trouble down to one stud. A careful investigation showed that the air gap under one of the two adjacent poles was about 8 per cent greater and under the other about 5 per cent greater than under the other four poles. This was evidently due to worn bearings caused by a combination of belt pull and the weight of the armature. This suggests a convenient way of isolating many machine defects.

A whole article might be written on commutator slotting. The best practise in commutator slotting consists in undercutting the mica about 3/64 in. below the surface of the commutator. It is of extreme importance that great care be exercised in slotting a commutator to see that all the slots are free from strips or particles of mica flush with the commutator. It is not advisable to use lubricant or artificially lubricated brushes on a slotted commutator, as the lubricant may get into the slots, collect dirt and cause short circuits between bars. On low-speed machines where the peripheral speed is not sufficient to throw out particles of dirt the commutator slots should be blown out or scraped out at regular intervals. On a slotted commutator a brush with no abrasive action may be used and will result in long life of commutator and brushes. A non-abrasive brush or a self-lubricating brush does not necessarily mean a soft brush. In fact, one of the hardest brushes manufactured in this country has been adopted as standard on slotted commutators by two of the four largest manufacturers of motors and generators in this country, and is rapidly being adopted by the other two.

Heating of the commutator on a machine may be caused by any form of sparking, short-circuit currents, friction of brushes, high brush pressure, too low brush pressure causing high contact loss, dirty commutator, overloads, too small commutator, resistance of windings, loose connections, eddy currents and hysteresis. As the ultimate capacity of a machine depends on allowable temperature rise it is important to prevent heating wherever possible.

Rapid wear of commutator may be due to abrasion by the brushes, presence of gritty dust, or any form of sparking.

Short life of brushes may be due to sparking, glowing, or mechanical wear caused by high brush pressure, dirt, high mica or a rough commutator.

OUTSIDE ELECTRICAL CAUSES

Outside electrical causes of commutation trouble may be briefly stated as overloads, line surges, and cross currents between two or more machines running in parallel. Where the angular speed of a reciprocating engine varies greatly, surges may occur due to a slight reduction in speed of motors on the circuit when the voltage is low and a consequent rush of current when the voltage reaches its maximum. It may be impossible to locate surges or cross currents without the use of an oscillograph.

OUTSIDE MECHANICAL CAUSES

If an armature is mechanically unbalanced severe vibration may occur, especially if run at high speed. This may produce flat spots, unbalanced electrical conditions, loosening of commutator bars and other serious troubles.

If the machine is on unstable foundations, similar troubles may be experienced due to vibration of the entire machine. In this class may be placed crane motors and similar machines, which are, however, usually designed with this factor in view.

Poor belt lacing or uneven gears may produce a vibration or strain with the same results.

The pound of a reciprocating engine direct-connected to a generator sometimes causes such a serious vibration that the brushes are thrown slightly from the commutator, causing sparking and flat spots.

In this paper no attempt has been made to guide the operator in the selection or testing of carbon brushes, or to discuss the effects of characteristics of carbon brushes, but the writer hopes to have the opportunity of presenting another paper on this subject.

DISCUSSION ON "SOME TROUBLES ENCOUNTERED IN THE OPERATION OF CARBON BRUSHES ON DIRECT-CURRENT GENERATORS AND MOTORS," (MARTINDALE), CLEVELAND, OHIO, MARCH 19, 1915.

D. B. Rushmore: Every designer of d-c. machines owes a debt of gratitude to Professor Arnold for his clear and careful elucidation of the phenomena of commutation. The phenomena are so exceedingly complicated, when you consider all the e.m.fs. involved, and all of the variables that can enter in the shape of quality and condition of the commutator and the carbon brush, the width, the pressure, distribution, and wear, etc. It was not until we got the little X-ray apparatus, known as the oscillograph, that we could begin to find out what was going on. The development of the electrical industry, and especially the d-c. machinery, is dependent upon this little carbon brush, and upon the peculiar qualities of contact resistance that we get with it.

One question I would ask Mr. Martindale is, whether there is anything else in sight, anything new in carbon brushes—any new construction of the carbon brush, which will help us reduce the design of electrical machinery to a point beyond the limitations imposed abroad. Direct-current machinery is not the only kind using carbon brushes now. The inherent nature of the a-c. motors running at constant speed is being diverted by the use of commutator motors to get variable speed. You will find in this city some large a-c. motors of this kind. What is the future possibility of improvement, of change, of substitution, of variation, in the manufacture of carbon brushes?

H. R. Edgecomb: Several points in this paper need to be particularly emphasized. The first is that the brush is the weakest link in the whole chain of connectors or conductors or joints in the machine.

The next point is the necessity of good mechanical conditions. It is surprising how little dimensional separation is required between brush and commutator surface to cause sparking and the resultant cumulative troubles. A brush rated to carry 30 amperes per sq. in. under ordinary running conditions, may carry five times that amount without distress, if the brush contact is mechanically right. The causes which are back of an intermittent separation of as little as one mil between the brush and commutator are many, and it is safe to predict that unless they are removed there will be trouble. It is futile to change resistance of windings, brush resistance or any electrical characteristics until these mechanical troubles are removed.

A gentleman just called my attention to the fact that he had a machine which he polished carefully, and the mica part was so hard that he got a separation between the copper and the mica, after having turned it. The very slight motion, the movement which it receives largely in turning, was sufficient to cause all the trouble necessary to put the machine out of business.

The third point is the cumulative effect of any disturbance which takes place at the contact surface of brush. Troubles of this class never decrease with continued service. For example, the heating of the brush makes it a better conductor, causes it to carry more than its share of the current, and this selective effect becomes greater until the brush finally glows and incapacitates itself and the commutator for further use.

What is the percentage effect of accumulated oxide or carbon deposits on the contact drop and friction? I mean by that, the cumulative effect in the test apparatus. What percentage effect have they on readings for contact drop and for friction? If you wiped the ring regularly with a clean cloth, would the percentage drop rise, and how much?

One more point, the danger of trying to identify commutator troubles by sound. I remember one machine on which the experts from two brush manufacturers spent nearly a week trying to solve the question of commutator troubles, or the brushing quality of the motor by sound and noise, and it happened one day the machine was started up without the d-c. brushes down and the noise was there just the same. The noise resulted from causes outside of brush contact or brush separation; it was a siren effect which came from the passage of air through the leads.

R. H. McLain: There is one cause of poor commutation that is not directly caused by the brushes, nor by any fault in the machine. I hope it is not getting too far away from the commutator to mention this cause of trouble. It is in the matter of control apparatus for motors which start and stop so frequently that the sparking which may occur during that period would seriously deteriorate the commutator, and get the brushes and commutator in bad condition or at least start them in the wrong direction, and allow the running of the machine after that to continue the deterioration. I think in hunting for commutator troubles you should not stop until you examine the control apparatus of a machine that is frequently started and stopped.

To illustrate some of the conditions, I know of a series-wound motor whose rated amperes are 200. The machine was reversed at full speed across the line, without any resistance in series, and it did not spark so that you could notice it. As near as could be told the current went up to 1100 or 1200 amperes, not by oscillograph, but ammeter. People would naturally pronounce that machine perfect as to commutation—you could not make it spark. However, if you used that same machine on dynamic braking, weakened the field enough to get it up to high speed, and then tried to stop it by short-circuiting the resistance in one step, you would get the worst form of sparking. Of course, in machines not as good as that particular one, if the resistance is not laid out for starting in the proper manner, you may have the proper number of switches to start the machine, the proper number of resistance blocks; but the peaks, being unequal and some extremely high, start commutating trouble.

I will give an example of a bad case of commutation caused by a controller. The motor was rated for 550 volts and about 300 amperes. The load in hoisting was about 300 amperes. The load in lowering was about 200 amperes. The lowering speed was 25 or 30 per cent above hoisting speed. It was stopped by the starting resistance. The first block of resistance that was cut out was exceedingly high. It was all right for starting purposes, but when it came to stopping the machine, you would have a machine running at 30 per cent over-speed developing momentarily 1100 volts and 900 amperes. It was a good motor, and had good brushes, but it sparked.

D. M. Petty: There is one point in connection with the discussion on carbon brushes which has not been touched on. It is the question of lubricants in the brushes. In the operation of a large number of machine tools we found that the motor builder used a brush impregnated with some kind of lubricant. After the brush has been in use for some time the lubricant is heated, runs out, and sticks to the brush holders. I feel that the brush manufacturers ought to be able to get out a brush with some kind of dry lubricant, so that the brushes would not stick to the boxes. The lubricant seems to be all right and serves its purpose very well, so long as it does not get on the brush holders, and the motor is kept running. As soon as the motor stops the brushes stick *up* in some position not in contact with the commutator, and when started next time the trouble accumulates.

The idea of the standardization of brushes, as brought out by Mr. Martindale, is one, it seems to me, all users of motors will welcome, because we find that almost every manufacturer has a different sized brush for even the same size of motor. If you have very many sizes and makes of motors in your plant, you very soon have to carry such a stock of brushes that it becomes a burden.

W. C. Kalb: Mr. Martindale spoke of the difference between hardness and abrasiveness, a very important point and one that is greatly confused. I have also found commutator wear resulting from brushes that were strictly non-abrasive when properly operated. I have felt, in the majority of these cases upon examination of the conditions, that it was due to a burning action. I know of one case where the brushes were operated under a very light tension. The result was pitting, the disintegration of the faces, such as Mr. Martindale described, a very dirty commutator and very high temperatures. In looking under the brush from the end of the commutator you could see an arcing condition there. That commutator was wearing badly, but by cleaning up the brush faces, and increasing the tension sufficiently to produce firm contact, it polished up nicely, and there was no further wear. The brush had absolutely no gritty material in it, so that the wear in that case must have been purely a burning action.

In the line of field troubles, there was a case I encountered on a large generator in which the brushes on certain studs would spark, and in the first attempt to remedy the trouble several kinds of brushes were tried, always with the same result. A further examination, however, showed that this machine had cast-in pole pieces; that is, the laminated pole pieces were cast into the frame, and the pole pieces themselves were unequally spaced. This introduced a condition that could not be entirely corrected by shifting the brush studs. You could shift them to correspond to the position of the pole pieces, but then you introduced a different number of armature coils between the adjacent studs. The displaced brushes had different voltages between different studs, and localized short-circuited currents between them, so that a compromise was all that could be had, and the best result could not be obtained for that condition, without reshaping the shoes of the pole pieces so as to equalize the spacing of the field poles.

The matter of the type of brush holder used is often a very important factor in the operation of the brushes. Mr. Petty referred to the trouble with lubricated brushes. Of course, the majority of manufacturers make brushes that are artificially lubricated, with some wax-like substance, possibly paraffine, possibly some other wax, and also brushes that depend on their graphitic make-up for lubrication and have no artificial treatment. A case such as he speaks of could undoubtedly be overcome by putting in a brush that had natural lubrication. This trouble is particularly pronounced on holders of the reaction type, where the brush is held against the plate of the holder by considerable pressure, the top of the brush being beveled, and the position of the spring or pressure arm being designed so as to bring a pressure against the plate. If these brushes are treated and operated at a temperature sufficient to drive some of the lubricating substances to the surface, when the machine stops, there is actually a freezing of the brushes; the material hardens and the brush is attached to the plate. It may be that, as it cools, the contraction of the ring will be such as to draw the brush away from the commutator, so that in starting up, one or many of the brushes will be actually out of contact. The result is that you start up with an arc, and as one man put it, you have a combined heating, lighting and power unit.

Another cause of brush troubles I have found at times, is with commutators that have been rebuilt or repaired, especially where it was necessary to loosen up the clamp ring. This applies to the type where the clamp ring screws on to the shaft and is not drawn in by bolts. In tightening this ring, the bars may have been given a twist, or it may be through carelessness in inserting mica, or otherwise, a little dirt has gotten in between certain bars, giving them an offset. Now, if a brush is covering approximately an even number of bars, that twist may be enough to throw them over on to an additional bar at one end, just as though the brush stud were crooked. That is often the cause of serious sparking, which can be overcome by care in clamping up the commutator and having the bars perfectly straight.

J. H. Lapp: In my opinion, the trouble is not so much in the brushes, as it is in the mica in the commutator. I had an instance of a machine which continued to spark. I set my brushes and did everything possible with the machine, and we could not get any better results—the machine ran at less than half load, with tremendous heating. I finally took the commutator out—it was a little flat on one side—turned it, and put it back in the machine, and it continued to spark and heat. I examined the mica bars and found the mica was so hard that in turning the commutator it seemed the tool just jumped over the mica bars and left them high. I took the bars all down, and the trouble was over, the machine running nicely.

L. P. Crecelius: I would like to say a few words in regard to a change in policy which is very noticeable on the part of brush manufacturers, and which seems to have taken place within the last three years. Before this period current densities of 30 to 35 amperes per sq. in. of carbon brush were about as far as we could carry the load on brushes. Now, however, considerably larger current densities are permitted, indicating that the subject of brush design has been seriously considered by the manufacturers, and seems now to be much better understood.

Recently in this city there were installed some fifteen 60-cycle synchronous converters, on which the commutators, principally on account of high speed, and partly also for economical reasons, were made very small in diameter, requiring therefore a very narrow brush, having fundamentally poor mechanical characteristics. Notwithstanding this serious limitation, proper brushes were subsequently found, but the point I want to raise is this: obviously the manufacturer of this electrical apparatus had entirely overlooked the fact that the brushes supplied with these machines were so weak that it was impossible to operate the apparatus. It was necessary for us to submit the difficulty to brush manufacturers who thereupon, after carefully studying conditions, submitted a design and the former brushes were replaced by the latter, with very satisfactory results, showing that it required but a small margin of improvement to bring about satisfactory conditions.

John P. Mallett: Of course, the size of the brushes is important, but there is another phase of the proposition which is also important, the pigtail problem. Mr. Martindale mentioned the possible standardization of the length of the pigtail, but the connection between the pigtail and the brush I have found to be an extremely important point. Most of you know that when any one wishes to remove a brush from the holder, he will take it out by the pigtail, and the result is the pigtail is liable to become loose. When it becomes loose the tendency is for it to become looser, because it burns from the poor contact. When it becomes very loose it is practically of no value, and if the design of the machine is such that the pigtail is required at all, you will get poor operation. Therefore, I think it is important that this question of the pigtail should be given careful consideration.

The point may be raised that certain manufacturers have patented methods of attaching the pigtail, and therefore, they would not deviate from those methods. That, again, will give rise to this condition—after such a machine has been in use for some time and new brushes are required a brush is obtained with some other kind of a pigtail, when the original is absolutely necessary. There is no question but that we can standardize on the pigtail, the method of attachment, etc., and it is quite as important as the dimensions of the brushes.

A. M. MacCutcheon: In regard to this point of standardization, the question has arisen in my mind whether the brush manufacturers are considering doing anything to reduce the number of kinds of brushes and narrowing down the number of qualities of brushes. We in the motor manufacturing business do not want the carbon manufacturers to reduce the number and kind of brushes if they cannot do so without interfering with the solution of our problems. We have many problems coming up which require different qualities of brushes, but if it were possible to reduce the number of qualities of brushes and still furnish as many answers in the solution of our various problems, we would be glad to see that done. I think our shop superintendents would be delighted if the engineers were not able to try as many different kinds of brushes on the motors as they do today. I would be glad to have Mr. Martindale inform us whether any action is being taken by the carbon manufacturers to try to reduce the number of qualities of brush, and yet be able to answer as many problems as arise. I do not suppose it would be a mistake to say there might be twenty-five or thirty qualities of brush. If you divide the 5000 brushes Mr. Martindale mentioned by the twenty-five or thirty, you have immensely reduced the number of different types.

E. H. Martindale: I think the discussion this morning has brought out the fact that there are many troubles not caused by the brushes.

In regard to standardization, I visited the works of a large manufacturer a short time ago and the gentleman to whom I was introduced said they would standardize on one length, two widths and five thicknesses. The length was to be 2 in.; the widths ¾ in. and 1¼ in., and the thicknesses ⅜ in., ½ in., ⅝ in., ¾ in. and 1 in. That reduces the possible sizes to ten.

I see no reason why practically every manufacturer could not adopt about ten, or at the most, fifteen standards, to meet the needs of all machines, except the small special machines, such as the dental motors and vacuum cleaner motors which will probably always have to remain special.

Mr. Rushmore asked if there was anything new in sight in brushes. There has been great development in the past few years in the manufacture of carbon brushes, and with the demands that have been made during the past few years in the manufacture of carbon brushes and with the demands that are being made by the manufacturer for higher current density and higher speeds it will be necessary to develop something else, or to limit the manufacture. If the machine will run at twice the speed, you can get nearly twice the power from the same weight. It is advantageous to get as high speed as possible. The turbogenerators have shown the great development which has been made in the capacity of machines of equal weight.

A great advantage of the carbon brush lies in its high contact drop with its comparatively high carrying capacity. The contact resistance of carbon brushes is approximately ten times the specific resistance. If we can find some material which will maintain the same contact drop as carbon brushes have at present with a resistance of half or less than the present carbon brushes, it will immediately give us something better to work on, provided it has the other characteristics of a carbon brush, such as long life and low friction. It is a question in my mind whether there is any other material that will answer that purpose.

Mr. Edgecomb and Mr. Lapp both spoke of the hardness of mica, and the difficulty of cutting mica with a tool. I think there is one point that may be of help in turning a commutator: it is that oil tends to reduce the cutting on copper and tends to soften mica. If oil were applied to the commutator perhaps several hours before the cutting is started, and then oil used during the cutting, the mica would cut down even with the copper much better than it does at the present time. However, this practise should not be generally recommended, as oil is a dangerous enemy of mica.

Mr. Edgecomb also asked regarding the effect of oxidation. The contact drop is a very difficult thing to reproduce exactly. It is largely due to the oxidation of the ring, but the method we have used is to let the machine run until the contact drop becomes constant. It may be fifteen minutes, and it may be three or four hours before you can get a contact drop constant. By rubbing a clean cloth over the ring, or your hand, or any object, a contact drop may go away up and it may go down. I have been watching a machine when there were no currents of air around and apparently nothing could change the contact drop, and it increased almost double. If we get any vibratory chattering of the brush, the contact drop will be greatly increased, due to the intermittent jumping of the brush from the commutator. The jumping is so rapid that with the ordinary volume of contact the voltage will seem constant; but it is more like the effect of the automatic voltage regulator, cutting in a high resistance, and cutting it in so rapidly that the resultant is of constant value.

Mr. Edgecomb also spoke of the noise due to air. I had a case at Defiance about two weeks ago where there was a click every time the commutator came around, that sounded like a high bar, but we could not locate it. We found the pigtails on the negative studs were vibrating. There were two pigtails on each brush, and at every revolution the two pigtails would come together, corresponding with that click; but we did not find out what it was.

Mr. McLain brought up the question of dynamic braking, which is a very serious problem. Its main use, in the experience that I have had, is in ore unloaders, where the bucket is going down to the boat and when nearly to the bottom the dynamic brake is used for quick stopping.

Mr. Kalb touched on the point which Mr. Petty brought up in regard to lubrication of brushes. Now, a great many users still insist on getting the cheapest brush they can buy. The cheap brushes are abrasive, from the materials which must be used, and the lubricant is put in largely to reduce the high friction. In the cheap brushes the material to be used for lubrication must necessarily be cheap in itself, and this will fry out under nearly normal conditions. Some lubricated brushes, that is, where the artificial lubrication is used, are made so that the wax will not fry out until the brush reaches a high temperature, higher than it should reach in normal operation. Lubricated brushes can be used if the machine has no short-circuiting current or other serious heating, which raises the temperature of the brushes.

As brought out by Mr. Kalb, however, it is better to keep away from any lubricant, on reaction type brush holders. I had a case where the commutator was about 1/32 in. out of true, slightly eccentric. Every night the brushes would freeze to the holders and in the morning the engineers would have to go around with a hammer and knock the brushes down on the commutator before starting. It was a shunt machine and could not give any voltage until this was done.

Mr. Petty spoke about a good many sizes of carbon brushes looking good to the carbon manufacturers, but it does not. It is impossible for the carbon manufacturers to keep brushes ready to ship, especially with the large number of sizes and grades used at the present time. If the sizes could be reduced to a small number, they could carry in stock brushes of all the sizes which are standard and ship them the same day that the order is received, instead of waiting a week or ten days. When material is carried in rough stock, which it must be with the present method, the material is sent to the first department, in which it is cut to the approximate sizes. After that it must be edge-planed, end-planed, and side-planed to exact size. At every machine there must be three to four orders waiting for the operator to work on; otherwise, if we tried to have a man working on every order as fast as it came, we would have to have about three times as many men as we could use in the low part of the load. It is a question of load factor of orders. On Tuesday, with the heavy mail received on Monday, we would probably need three times as many men as in the rest of the week.

The points brought out by Mr. Kalb were very interesting, especially oxidation and the unequal spacing of cast poles.

Mr. Mallett spoke of the standardization of the pigtail connection. We would like to do that very much, but all the good ones are patented, either by us or some one else. We cannot standardize a patented pigtail connection. Something might be done in standardizing pigtail connections by limiting the voltage drop between the brush and the pigtail to a certain definite value; and, as a further specification, making the pigtail mechanically secure in add tion to a low-resistance electrical contact, so that after long operation the pigtail will still be intact.

Mr. MacCutcheon spoke of the number of different kinds of brushes. We have fifty-two at present that are commercial, and quite a number of laboratory brushes on test. We hope to have fifty-seven pretty soon. I do not know that I should say we hope to have, but we probably will have. It is not necessary to have so many kinds of brushes as we have, from an operating standpoint, but it is from the carbon manufacturer's standpoint, because there are more than that many variations. There are at least six or eight different kinds of coke used in brushes, and at least fifteen or twenty different kinds of graphite. All these graphites have a different ash, and it is the ash constituent that largely influences the brush in regard to friction and abrasive action. The ash in the graphite may be mica, or quartz, or iron oxide, or silica, or any one of several other materials which are ordinarily found in graphite. The reason we need so many different varieties is because somebody sends in a brush and says " please send us so many brushes per sample, of such a grade." We carry a great variety of brushes, and can duplicate any brush on the market. That is the reason why we have so many, and not because they are needed from an operating standpoint.

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FRACTIONAL HORSE POWER MOTOR LOAD

BY BERNARD LESTER

Abstract of Paper

In this article the author outlines the broad and increasing use of fractional horse power motors and the chief causes for the advance in popularity of motor-driven machines. The success in this field of motor application has been largely due to the perfection of a reliable and simple single-phase motor. The development in the design and construction of the single-phase motor is traced from its origination to the present time, and the operating characteristics of the commoner types of single-phase motors are described and illustrated by the use of speed-torque curves. The correct application of small motors is of utmost importance and requires a careful analysis of motor characteristics, the characteristics of the driven machine and of the supply circuit, with the limitations of each. The author deals particularly with the characteristics of the split-phase induction motor, which is used so extensively, and points out the functions of the centrifugal clutch when employed as a component part of this motor. A reference diagram is presented which is of service in applying small motors.

IN TECHNICAL literature very little space has been devoted to the discussion of fractional horse power or small motor load. The subject presents certain difficulties of approach, perhaps on account of the close association of the commercial and engineering aspects, which cannot easily be divorced from one another. Furthermore, there is a tendency on the part of the engineering profession to consider, since the power-producing units are so small and they are applied to such ordinary devices or machines, that the problems met in applying these motors are not strictly those which should concern an engineer. The purpose of this paper is to show briefly the extent of this rapidly growing field, and that in it real engineering problems exist which deserve most careful analysis.

When we consider that few motors were used in the industrial field prior to 1890, we realize, in a measure, the rapidity of the growth of the industry, but it is not until we classify the industrial field of motor application, and see what has been done in the various industries, for example, in the steel mills, paper mills, textile mills and machine shops, that we can realize the development of motor application and can fully account for its growth. During the last ten years the field for the use of fractional horse power motors has increased enormously and many new devices have become available commercially. Typical examples of small motor applications can be found in residences, stores, offices and workshops. This list varies from motors used to drive vacuum cleaners, washing machines, meat and coffee grinders, and sewing machines, to those used in portable drills, railway signals, and the most delicate laboratory instruments.

There have been three principal causes for this development in the small motor field:

1. Efficiency engineering in every field of endeavor has brought to the mind of the public the realization of the saving that can be accomplished in time, labor and money by operating small appliances electrically.

2. Wide distribution of central station circuits, primarily for the purpose of lighting, has greatly increased the possible field for the use of small motors.

3. The performance of the small motor as a reliable source of power, and its proper application, have established the confidence necessary to encourage the investment of time and money in the development of the industry.

Savings in time, labor and operating cost by the use of small motor-driven machines can best be illustrated by reference to several very common small motor applications. In the dwelling, the small motor-driven washing machine, vacuum cleaner, ironing machine and sewing machine shorten the time required to do the work, and materially decrease the amount of manual labor required, besides increasing the quality of the work and the convenience with which it is done. In the office, motor-driven calculating machines, and machines for addressing, sealing and stamping mail matter or tying packages, are now becoming common, on account of the fact that they in the aggregate save a large amount of time on the part of the office force, or in reality increase the productive labor of the individual. In the blacksmith's shop, for instance, motor-driven forge blowers have taken the place of the old cumbersome hand-operated bellows. The store or meat market is now often equipped with a meat grinder, meat slicer, coffee grinder or coffee roaster. These make possible economies in the preparation of products for sale.

It will be noted that in all these cases the success of the device depends upon one or more of the three general features possessed by the small motor, *i.e.*, simplicity in starting and stopping, portability, and continued operation without frequent attention.

The remarkable extension in central power station lines in cities and suburbs needs no further comment here, other than to point out that the majority of small motor-driven machines are of such capacity and characteristics that they are suitable for connection to lighting sockets.

Since single-phase alternating-current distribution is so largely employed for lighting and consequently is available as a supply for small motor-driven machines, the development of a simple, reliable and efficient small single-phase motor has had a large share in the growth of this industry. Single-phase motors of the series, repulsion or induction type, or some modifications or combinations of these principal types, have been largely used.

Series Motor. The series-wound single-phase motor, due principally to its varying speed with change in torque, has a limited application. Obviously it can only be safely used where the load is rigidly connected to the driving shaft of the motor and where large variations in speed are permissible with variations in load. This type of motor is very successfully used with fans, where the fan is attached to the motor shaft, and is used for exhausting or supplying air, as in the case of most fan type vacuum cleaners or forge blowers. Also for portable electric tools, in which case the power is turned off when the tool is not in actual service. Its use, however, is limited to these or similar applications. A great advantage in the series-wound motor, when especially constructed, is that it can be operated upon direct current or alternating current of most commercial frequencies, and the same voltage, with speed-torque characteristics sufficiently similar to produce results generally satisfactory in motors of small capacity. Obviously, there is a great commercial advantage in a motor-driven device that can be operated either on alternating current or direct current.

The single-phase repulsion motor, which is a modification of the series motor, possesses in general the same limitations in regard to its speed-torque characteristics as the series motor. However, without load it does not attain the same dangerously high speed. Since the brushes are short-circuited the universal feature, *i.e.*, the possibility of operation upon alternating-current or direct-current circuits, does not exist.

Induction Motors. The single-phase induction motor possesses a speed-torque characteristic in which the speed holds practically constant under a varying torque and is excellently suited for the large majority of small motor-driven machines, provided a means is supplied to bring the rotor or secondary element of the motor up to a speed at which the inherent torque produced by the motor is sufficient to accelerate the load.

The split-phase induction motor is by far the most common type of single-phase motor used in fractional horse power sizes. Since in its development the most difficult problem has been in overcoming the absence of starting torque in the simple single-phase motor, the principal steps in this development will be mentioned.

The first split-phase self-starting motor was developed by Tesla and was used for driving small desk fans, but was not employed generally for power service. Several years after this, about 1893, single-phase induction motors of larger capacities were developed and used, but since there was no device for starting the motor, it had to be started by hand—and like any polyphase induction motor when connected to a single-phase circuit, and operated on one phase only, would run in either direction if started by some external force and accelerated to a point at which the torque developed by the primary of the motor upon the rotating element was sufficient to carry the rotor up to speed. The speed-torque curve of such a motor is shown in Fig. 1, curve *AD*. From 1893 to 1895 self-starting split-phase motors were designed with two windings in the primary, one of which was employed primarily while running, and the other only for the purpose of starting. A phase splitter consisting of a manually-operated external switch and resistance, connected the primary windings to the supply circuit, inserting resistance in the starting winding. A phase displacement in this way existed between the currents in the two windings, which exerted a torque upon the rotor in starting, the starting winding and resistance being manually cut out as soon as the

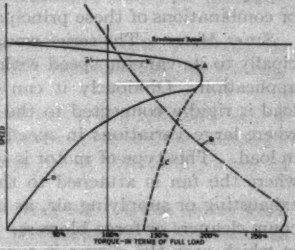
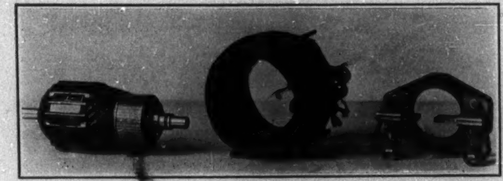


FIG. 1



[LESTER]

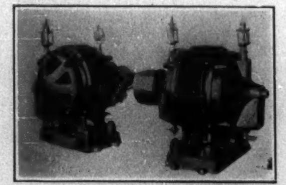
FIELD, ARMATURE, AND BRUSH RIGGING OF HIGH-SPEED SERIES-WOUND UNIVERSAL MOTOR FOR VACUUM CLEANERS AND ELECTRIC DRILLS

[LESTER]

TYPICAL AUTOMATIC SWITCH OF LATEST DESIGN, USED WITH SPLIT-PHASE MOTOR; SHOWING CENTRIFUGAL ELEMENT MOUNTED ON ROTOR

[LESTER]

TYPICAL MULTIPLE DISK CENTRIFUGAL CLUTCH OF LATEST DESIGN USED WITH SPLIT-PHASE MOTOR



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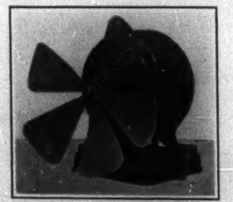
1-H. P. TWO-PHASE TESLA MOTORS



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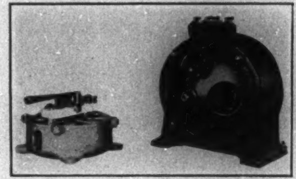
SPLIT-PHASE FAN MOTOR



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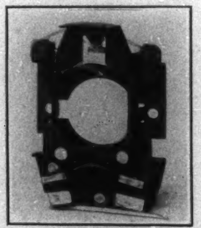
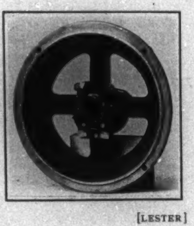
¼-H.P. Single-Phase Motor with Phase Splitter



[LESTER]

Typical Automatic Switch of Latest Design, Used with Split-Phase Motor; Showing Stationary Element in Position when Starting Winding is Open



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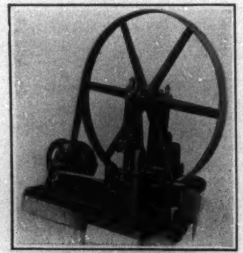
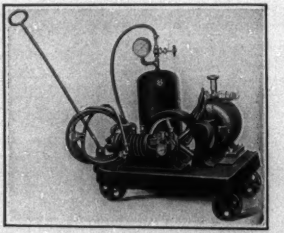
Stationary Element of Centrifugal Switch Mounted upon Motor Bracket



[LESTER]

Motor-Driven House Pump



[LESTER]

Motor-Driven Automobile Tire Pump

motor came up to speed. Somewhat later, motors were designed with which were used starting devices supplied with a condenser in place of a resistance. This device produced a greater angular advance in the phase displacement than was the case with the resistance starter. In this particular, therefore, a somewhat improved operating characteristic was obtained due to higher power factor of the motor—the condenser remaining in the circuit while starting and running.

About 1898 single-phase induction motors were designed which started as series motors. The secondary winding was similar to that of a series motor, the commutator bars being short-circuited as the armature accelerated, after which the motor ran as an induction motor. Shortly after this an advantage was found in starting as a repulsion instead of a series motor, since the motor so constructed could be connected externally for use either upon 110- or 220-volt circuits. Motors designed in accordance with this principle are now widely used, especially in sizes above ½ h.p. An automatically operated centrifugal governor within the rotating element short-circuits the commutator bars. Fig. 1, curve *B*, shows the speed-torque characteristics of such a motor while starting, in approximately the relative position to the induction motor, curve *AD*. The light line *ab* represents the speed at which the motor automatically switches from a repulsion to an induction motor.

Another development in the split-phase motor was in the use of an external clutch or clutch pulley. Due to the difficulty in obtaining in the earlier designs sufficient starting torque to enable the motor to be used for accelerating other than very light loads, centrifugal clutches were used which allowed the rotor and shaft to accelerate to a point at which a liberal torque was exerted by the rotor, at which point the clutch took hold and applied the load to the motor. Within the last few years marked improvements have been made in the design of split-phase motors. Sufficient starting torque can now be obtained without the use of a centrifugal clutch, for many classes of small motor service. A light, high-resistance starting winding in addition to the running winding is used. Fig. 1, curve *AC*, shows a typical speed-torque curve of a no-clutch split-phase motor of recent design. This starting winding is cut out by means of a very simple and reliable centrifugally operated switch placed within the motor, at a speed slightly below full load. The centrifugal clutch when used is of simple construction and is placed within the motor, the rotating element revolving upon the shaft until its speed reaches a predetermined point at which the clutch takes hold.

Various modifications have been made in the repulsion motor, intended to make its speed more nearly constant with varying loads, and also improve its power factor, by means of extra brushes on the commutator and auxiliary windings in the primary.

Since so many motors of one particular size and type are used, designs must be adapted for economic quantity manufacture and uniform performance consistent with such apparatus. Furthermore, since motors of special mechanical and electrical characteristics are often required, standard designs must be adapted to provide for such modification without a complete redesign of the motor. Fractional horse power motors must be neat and attractive in appearance since they are used in the home, office or shop in connection with, or as a part of, a machine which is usually highly finished. Lightness of weight and compactness of construction are of considerable importance, for many small motor-driven machines are of a portable or semi-portable character. Quiet operation is always desirable and often absolutely necessary in cases where these motors are used for the operation of musical or talking machines. In the last few years it has become common practise to design direct-current motors with full-load speeds corresponding to those of 60-cycle alternating-current motors. Furthermore, for equivalent ratings in alternating-current and direct-current motors similar mechanical characteristics have been adopted, so that either an alternating- or a direct-current motor can be mounted in identically the same place in relation to the driven machine, thus simplifying the construction of the motor-driven machine.

Small motor applications fall into four thoroughly well defined classes, depending upon the length of the operating period and the variation of the load while in service, *i.e.*:

1. Motors operating continuously, with approximately constant load; for example, ventilating fans and forge blowers.

2. Motors operating continuously with varying load; for example, sign flashers and most adding machines.

3. Motors operating intermittently, with constant load; for example, coffee grinders and most automatic piano players.

4. Motors operating intermittently, with varying load; for example, household washing machines and ice cream freezers for household use.

It is interesting to note that small-motor engineers encounter almost identically the same problems as those of the engineer applying larger industrial motors, in so far as cycles of operation and speed-torque requirements are concerned. For instance, in the application of small motors to washing machines with wringers, the wringer is the limiting feature, taxing the motor with sudden peak loads. This application may well be compared to that of a motor-driven rolling mill. The motor-driven meat grinder compares closely with the motor-driven pulp mill beater, and the coffee grinder with the rock or stone crusher. In the design of high-speed motors for fan-type vacuum cleaners, the problems closely parallel those of the high-speed turbo blower.

Hundreds and even thousands of motors of one particular type and size may be applied to a particular type and size of driven machine, consequently, a very careful analysis should be made to secure the correct drive. Failure may come when operating conditions cease to be ideal, should a motor of insufficient margin of safety with regard to the essential electrical and mechanical characteristics be employed, and the expense of such failure cannot well be estimated when we consider that these small motor-driven machines are scattered broadcast. In the interests of economy, however, an abnormal margin of safety is objectionable. The question of the selection of the proper characteristics is largely, therefore, a consideration of limiting conditions of operation. The following general points should be considered:

Variation in the essential electrical and mechanical characteristics of duplicate motors, incident to their manufacture in quantities.

Variation in the value of torque required to start and power to operate duplicate driven machines, incident to their manufacture in quantities.

Variations in the characteristics of the circuit on which the motors are to operate, such as variations in voltage, frequency or both.

In applying split-phase motors, aside from the general characteristics outlined elsewhere, special attention must be given to those characteristics of starting torque, pull-out or maximum torque and temperature rating. The starting torque varies approximately as the square of the impressed voltage, consequently any reduction in the voltage of the circuit at the motor produces more than a proportional reduction in torque. Furthermore, the starting current of split-phase motors materially exceeds the full load running current. This factor, in addition to light wiring or insufficient transformer capacity, often results in a reduction in starting torque of the motor in the average commercial installation. Good practise in small motor application provides that the motor should be able to start the driven machine when the impressed voltage is as low as 20 per cent below the rated voltage. A centrifugal clutch is often incorporated in the design of the motor not only to insure an ample starting torque and reduce the effect of the current taken during starting, principally by cutting down the time during which it is taken, but also to provide an element of flexibility in the case of a machine rigidly connected to the motor. The clutch will slip in the event of sudden or extreme overload, thus protecting the combined unit.

Fig. 2 will give an idea of the comparative values of the current and its duration taken by split-phase motors during starting. These curves are oscillograph records. Curve *A* represents a motor without centrifugal clutch, driving a generator, and curve *B* is for a motor of equivalent capacity and speed, equipped with a centrifugal clutch, operating under similar conditions. The latter motor is supplied with a different starting winding, being permissible where a clutch is used. It should be noted that rulings prohibiting the use of single-phase motors upon lighting circuits, based upon the amount of current taken by the motor while starting, are misleading when expressed in terms of full-load current taken by the motor. For example, though the starting current of a ½-h.p. motor may be only three times as great as the full-load current, its value may exceed that of a ⅙-h.p. motor, even though the starting current taken by the latter may be five times its full-load current. It seems reasonable that such rulings should specify in amperes the permissible current which motors may take, corresponding to the established voltages.

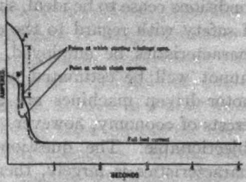
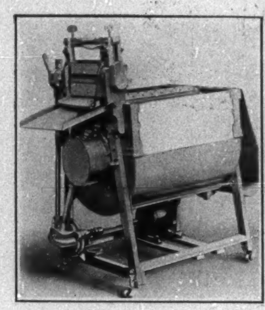


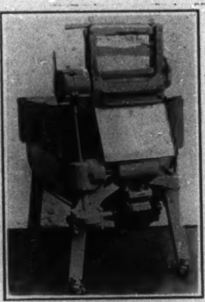
FIG. 2

The pull-out or maximum torque of the motor must obviously be sufficient to take care of any peak loads to which the motor may be subject in driving the machine, even at voltages somewhat lower than the normal rated circuit voltage.



[LESTER]

MOTOR-DRIVEN WASHING MACHINE



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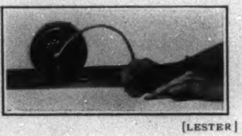
MOTOR-DRIVEN WASHING MACHINE



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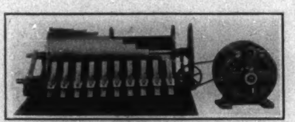
MOTOR-DRIVEN ERASING OUTFIT



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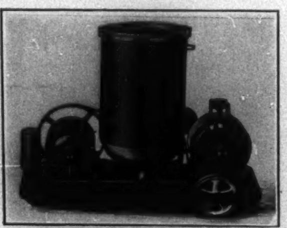
MOTOR-DRIVEN SIGN FLASHER



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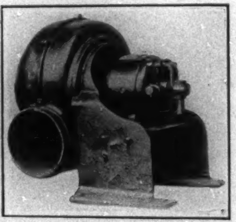
MOTOR-DRIVEN VACUUM CLEANER



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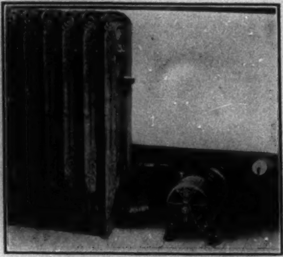
MOTOR DRIVEN BLOWER

PLATE XL.
A. I. E. E.
VOL. XXXIV, 1915

[LESTER]
MOTOR-DRIVEN EXHAUST FAN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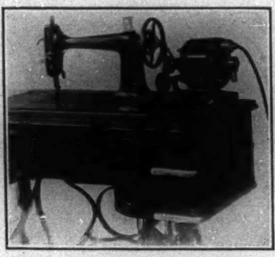
MOTOR-DRIVEN VENTILATING OUTFIT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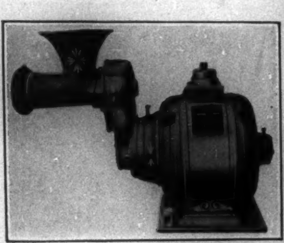
MOTOR-DRIVEN SEWING MACHINE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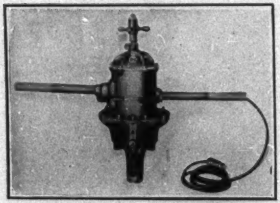
MOTOR-DRIVEN MEAT CHOPPER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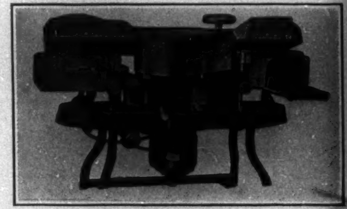
MOTOR-DRIVEN DRILL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MOTOR-DRIVEN MAILING MACHINE

Many small motor-driven machines are not ordinarily called upon to operate continuously, but only for short intervals, with prolonged periods of rest intervening between operating periods. Obviously, in these cases intermittently rated motors may be employed. However, unless the cycle of operation is well defined by practise, it is well to use a motor so rated that it will run the machine continuously without attaining a dangerous temperature. Sometimes the machine may be left running by mistake. Small motors of commoner designs and capacities will attain their maximum temperature in from two to five hours. Commercially it is not permissible with most small motor-driven machines, particularly those in domestic service or in stores and offices, to employ motors so rated that they will attain a temperature as high as the insulation will safely stand, for the motor becomes appreciably hot to the touch and creates suspicion.

The starting torque and pull-out torque of fractional horse power motors are usually measured in ounce-feet. The diagram shown in Fig. 3 (which is here reduced in size) has been prepared, covering the various characteristics of fractional horse power single-phase and polyphase motors, and is useful for purposes of reference. The following illustrations will indicate how it may be employed in small motor application work.

Knowing the Horse Power and Speed at Full Load, to Determine Full-Load Torque. For example, find the full-load torque of a ¾-h.p. motor running 1700 rev. per min. at full load (1800 rev. per min. synchronous speed). Find the intersection of the vertical line through 1700 rev. per min. with the curve marked ¾ h.p. (560 watts), and horizontally opposite this intersection at the left is the torque, 36.5 oz.

The Starting Torque and Maximum Running Torque can be found by multiplying the full-load torque by the proper constants. For example, if the starting torque of this particular motor is 1.5 times the full-load torque, its value is $1.5 \times 36.5 = 55$ oz. Likewise if the maximum running torque of the motor is 2.5 times the full-load torque, its value is $2.5 \times 36.5 = 91$ oz. These constants must be determined from the characteristic curves of the individual motor.

The Horse Power at Maximum Torque can also be determined from the curve if the speed is known. For approximate results the slip of small split-phase induction motors at maximum torque can be taken at 15 per cent. In the case of the above motor

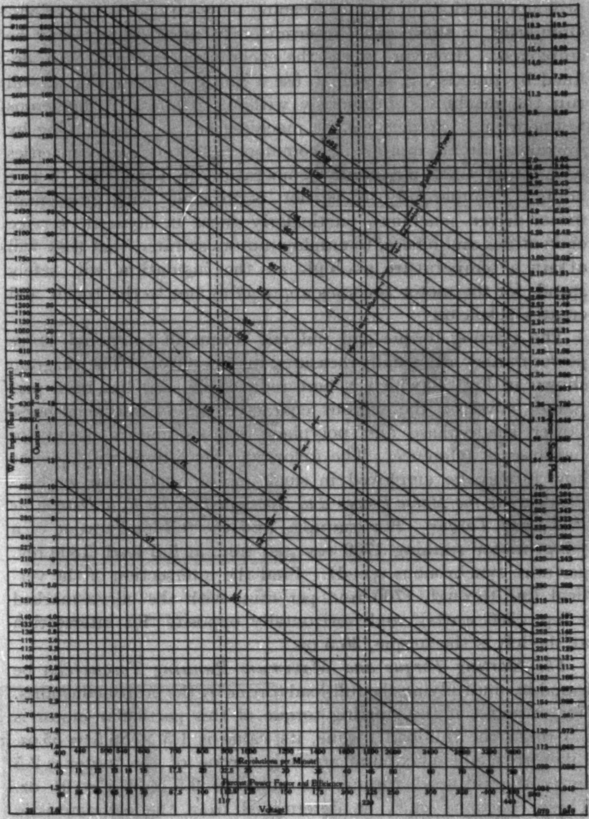

Fig. 3—Chart for Determining Relative Characteristics of Small Induction Motors

For current in two-phase motors, take half the value indicated for single-phase motors.

the speed at maximum torque will therefore be approximately 1450 rev. per min. Find the intersection of the vertical line through 1450 rev. per min. with the horizontal line through 91 (oz. torque). This is near the line representing 1.5 h.p., which is the approximate power developed by the motor just before pulling out, or stalling.

Knowing the *Horse Power and Efficiency*, to find the *Real Watts;* for example, assume that the efficiency of the ¾-h.p. motor is 75 per cent. Find the intersection of the vertical line through 75 with the ¾-h.p. curve and horizontally across from this intersection is 746 watts.

Knowing the *Real Watts Input*, the *Power Factor* and the *Voltage*, to find the *Current per Phase* (or per terminal); for example, assume that the power factor of the foregoing motor is 70 per cent and the voltage 220 volts. Locate the intersection of the 70 per cent power factor vertical line with the diagonal representing 746 watts. The horizontal line passing approximately through this point represents 1050 watts apparent. Then from the intersection of the vertical line representing 220 volts with the diagonal representing 1050 watts, the horizontal line representing amperes is determined, namely 4.8 amperes, single-phase, or 2.8 amperes three-phase. The current per terminal in a two-phase motor is one-half that for a single-phase motor, and in this case would be 2.4 amperes.

DISCUSSION ON "FRACTIONAL HORSE POWER MOTOR LOAD," (LESTER), CLEVELAND, OHIO, MARCH 19, 1915.

G. H. Garcelon: Mr. Lester, in his paper, has brought out a point that will bear further discussion; namely, the question of selecting a motor to operate a given device and give the best all-around service when used on the different circuits encountered over the wide area in which motor-driven devices are applied.

Motors manufactured and sold in quantities for application to motor-driven devices to be marketed broadcast must necessarily follow some standard. This is true from the standpoint of economical manufacture by the electrical company and also from the standpoint of the stock carried by the resale manufacturer at his factory and his various agencies.

The sale of motor-driven devices with motors wound for special voltages or frequencies is unprofitable for both manufacturers.

On this account, motors for this class of service and of sizes suitable for operation from lighting circuits are generally rated at 110 volts 60 cycles, or 115 volts direct current. Inasmuch as by far the greater percentage of fractional horse power motors is operated from single-phase a-c. circuits, the following points will bear on this type, although they may be applied equally well to d-c. motors, with certain limitations.

Most lighting circuits supply current at 110 volts 60 cycles, but there are circuits rated at 104 volts and even as low as 100 volts. On the other hand, 120-volt circuits are frequently encountered.

Of course it is impossible to maintain a uniform voltage throughout a distributing system, which again results in voltages varying from standard. Circuits which are loaded at times to their full capacity and often beyond it, give rise to varying voltage at a given point. The current drawn by a motor at starting and on overload also causes an additional drop in voltage in the local circuit and variations under the different conditions.

For the foregoing reasons a motor must be designed to satisfactorily operate the device to which it is attached under conditions which are far from ideal. Unfortunately the torque developed by a motor varies as the square of the voltage applied to its terminals, so that at 90 per cent of its rated voltage it develops but 81 per cent of its normal torque. This is particularly detrimental under starting and maximum load conditions. Furthermore, the voltage at the motor terminals is lowest, due to local line drop, when high voltage is most needed, namely, at starting and on overload.

From a consideration of these points it is evident that, to give universally satisfactory service, a motor must not only have sufficient capacity to handle its attached device under very unfavorable conditions due to low voltage, but also must contain a liberal amount of active material so that it will not be injured by voltages above normal.

From the experiences of the manufacturers of motors and motor-driven devices it has been demonstrated that motors for this class of service should be so applied that, on the basis of 110-volt rating, they will satisfactorily handle the device under its maximum load at 90 volts and also operate on 120 volts without injury to the motor. This means that a motor operating on the highest permissible voltage must have torque approximately 80 per cent in excess of that required to perform its normal functions.

Coupled with this, consideration must be given to the effect of manufacturing variations in both motor and driven device, as already pointed out in Mr. Lester's paper. These variations will be at least 10 per cent in each case, which gives the condition that the best motor, on the best device, at maximum voltage, is at least twice the capacity that would be required under ideal conditions. On the other hand, care must be exercised to keep the capacity of the motor to a safe minimum in order to produce a motor having the lowest cost, best performance, lightest weight and smallest starting current consistent with safe and reliable operating characteristics.

As previously stated, the prevailing alternating-current lighting circuit is supplied with 60-cycle current, but many circuits are encountered which show variations in frequency, as well as circuits rated at 60 cycles which are in reality several cycles higher or lower. While such variations are a smaller percentage from standard than the voltage variations, and consequently of less effect on a motor, yet they must be considered in its design and application.

Variations in frequency have effects on the torque of a motor similar to voltage effects but, as previously mentioned, the percentage variation is smaller and is generally disregarded in the design of a motor, as far as torque characteristics are concerned. It is assumed that the allowance for voltage variations will give sufficient margin of safety.

Manufacturers of motor-driven fan-type blowers of any kind must give this point consideration, however, owing to the rapid increase in power required when the speed of the fan is increased. The speed of most widely used single-phase motors is a function of the frequency and the torque varies inversely as the square of the frequency. From this it follows that high frequency not only increases the load but decreases the torque available. The principal cause for giving variations in frequency careful consideration in the design of a motor for a given device arises from the fact that most commercial motors for single-phase operation employ one or more centrifugally operated auxiliary devices used for starting; such as switches, governors, clutches or some combination of the three.

These devices are designed to operate at some predetermined speed bearing a definite ratio to the synchronous speed, which is of course fixed for a given motor by the frequency of the supply circuit. Hence, if the frequency differs from that for which the device is designed, the ratio of its operating speed to the actual synchronous speed of the motor is altered, and the operating characteristics of the motor variously affected, depending upon the function of the centrifugal device or devices employed. This feature is one which is primarily the problem of the motor manufacturer but should be borne in mind by the resale manufacturer when it is known that a machine is to be operated on a circuit varying from standard frequency. Consultation with the motor manufacturer is to be recommended in such cases unless previous experience with the same type motor has demonstrated that the variation has no detrimental effects.

All these factors, coupled with the zeal of the resale manufacturer to obtain the cheapest possible motor-driven outfit, render the application of a small motor to such apparatus a real problem and make it highly desirable to have the application made jointly by the engineers of both manufacturers.

Presented at the 306th meeting of the American Institute of Electrical Engineers, Cleveland, O., March 19, 1915.

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THE FACTORS INVOLVED IN MOTOR APPLICATIONS

BY DAVID B. RUSHMORE

THE work of applying electricity to industrial operations consists in properly combining the motor, controller and machine to be driven. This involves the characteristics of all three and a number of other features which are concerned more or less in the particular situation.

The following is a list of some of the factors involved and is intended to be used as an introduction to a discussion on the individual features concerned.

SUMMARY OF THE FACTORS INVOLVED

1. Alternating or direct current available?
2. Voltage and frequency (if alternating current)? Possible variations in same?
3. Capacity of generating station and lines? Other load on systems? (This information is required for determining effect of starting).
4. Description of machine to be driven? Continuous or intermittent service? Can intermittently operated machines be arranged as to not operate simultaneously? Limited speed?
5. Method of drive. Group vs. individual. Direct connection (Size of coupling, rigid or flexible, insulated? Shaft extension, sub-base, etc.)
    - Belt drive (Size of pulley, distance between pulleys, outboard bearing, belt tightener?)
    - Chain drive (Size of pinion).
    - Gear drive (Size of pinion).
    - Friction drive (Is motor to be started light and clutch thrown in when motor is up to speed?)
6. Load conditions.
    - Continuous?

Cycle-duty, in which a definite cycle repeats itself with more or less regularity, the machine stopping after each cycle?

Varying-load duty, in which more or less definite cycles are repeated, but motor runs continuously?

(Load diagram required during a complete cycle of operation. This gives the maximum horse power, length of load on, time off and friction load).

Can any parts of cycle be varied with benefit?

Variation in load caused by change of conditions, such as decrease in the head on a centrifugal pump. Allowance must be made in the motor size to take care of such contingencies.

Future conditions? Is it possible that the load on the motor may be soon increased? Motor speeded up? Flywheel effect required?

7. Starting conditions.

Frequent starting, stopping or reversing?
  (Number and time off?)
  Time of acceleration?
Does load on motor increase as it comes up to speed?

8. Speed.

Is close speed regulation essential?
Constant speed?
Adjustable speed?
Varying speed?
Multi-speed?
Speed range required?
At reduced speed, is horse power output reduced in proportion to speed (*i.e.* constant torque)? If not, give the proportion.

9. Control.

Hand or automatic?
Remote?
Overload or no-voltage release?
  (Time setting?)
Limit switches?
Brakes?
  (Mechanical or electrical?)
Stopping of large motors?

10. Conditions of location.
    - Dust, moisture, acid fumes, inflammable material, high temperature, etc.?
    - Ventilation?
    - Space conditions?
        - (Method of mounting motor, access for repairs, etc.)
    - Safety arrangements?
    - Insurance regulations?

DISCUSSION ON "FACTORS INVOLVED IN MOTOR APPLICATION," (RUSHMORE), CLEVELAND, OHIO, MARCH 19, 1915.

THE FACTORS INVOLVED IN MOTOR APPLICATION, WITH PARTICULAR REFERENCE TO THE RUBBER INDUSTRY

A. P. Lewis: Within the last five years the impetus received by the rubber industry has necessitated special motor applications to facilitate production. The first installations, however, developed the fact that there were several conditions to be met which differentiated the drives from certain standards assumed.

Not less than 75 per cent of the total energy in the form of mechanical motion is utilized in the treatment of the crude material before it reaches a condition where manipulation is dependent upon the product. It might be inferred, therefore, that the engineer would encounter his major problems in these stages of the manufacture, and such is the case.

There are three kinds of machines for advancing the process which require special motor applications, viz., washers, mixing and warming mills, and calenders. While the functions of the washers and mills are not the same, their design and load characteristics are similar and may, therefore, be merged when considering driving units.

A brief digression may not be inopportune to acquaint those unfamiliar with the action of these machines.

All wild rubbers have foreign matter in them held in physical suspension. It is the work of the washer to remove this. The machine consists of two end housings, and journals which carry two rolls in a horizontal plane, whose surfaces are riffled, and which are turned at different surface speeds. The rubber, in pieces, is passed between the rolls, while water is played on it, and the tearing action soon liberates the dirt, which is washed out. These machines are always operated at a constant speed.

After the rubber has been thoroughly dried, it has to be mixed with sulphur and other ingredients to give the vulcanized product the qualities desired. This mixing is accomplished on a mill which is much like a washer, but of larger proportions, and with smooth rolls. These mixing mills are also operated at a constant speed.

Following the seasoning period, it becomes necessary either to sheet the rubber out in a variety of ways, or to apply it to fabric. This is done on a calender, which usually consists of three or four superimposed rolls, which may be run at the same or different surface speeds by means of end roll pinions. These rolls are capable of very fine adjustment. The ability to vary the speed plays a very important part in the efficient working of the rubber calender.

With this brief digression concluded, it may be noted that the principal motor applications simmer down to two in number, one for constant speed, the other for adjustable speed, but both for heavy duty.

Reference may now be made to Mr. Rushmore's complete synopsis by number, with reference to design of the mill or washer driving unit.

1. *Alternating or Direct Current Available?* We will assume that alternating current is available, as it is the logical system to use for several reasons.

(a) Over 60 per cent of the electrical energy is transformed to mechanical motion by constant-speed motors.

(b) Central station energy may be utilized with minimum loss.

(c) Large blocks of power may be transmitted efficiently.

(d) First cost and maintenance of the system is lower.

2. *Voltage and Frequency.* The potential should not be less than 440 volts in the system, and 2200 volts may be advisable, stepping down, if necessary, for building or departmental distribution. A standard frequency of 60 cycles, should, I believe, be rigidly adhered to. Some few years ago there may have been arguments in favor of 25- or 30-cycle systems in plants using synchronous converters, due to their superior operating characteristics at low frequencies. The advance of the art has remanded those arguments.

3. *Capacity of Generating Station and Line.* This particular feature will vary with each instance, and need not be elaborated on. As in nearly all industrial applications, the generating station may be assumed to be working at or near capacity, and therefore starting currents for large motors are limited.

4. *Description of Machine to be Driven.* The function and brief description of washers and mills has already been presented. They are direct-connected to a line shaft turning from 80 to 100 revolutions per minute, and the mode of operation is such as to require motors designed for continuous service. The speed of the mills or washers is limited by two features, first, by the action of the rolls on the rubber and the ability of the operator to handle the stock properly, and secondly by the mechanical limitations of excessive wear and vibration. High speed on rubber machines, as designed today, is of questionable value, as maintenance costs rise out of all proportion to the product passed.

5. *Method of Drive.* The individual drive for rubber machines of the class being discussed should not be considered where avoidable. The very apparent reasons are ones of first cost, floor space, and motor efficiency. On the other hand, too wide a limit must not be exceeded in a group drive, or maintenance cost will go up. I believe that the most economical rubber mill drive contemplates the use of not over eight mills per motor, with preferably six. With this number, the drive shaft length is restricted, distortion is negligible, and with properly designed mechanical appliances, repair costs are practically nil.

All troubles on mill drives with which I am familiar may be traced back to mechanical deficiencies, excessive vibration, mis-alignment, shaft-whipping, or eccentricities, all of which act cumulatively, and revert to the motor with disastrous results. I mention these points to impress the close relation between mechanical and electrical problems.

The low speed of the line shaft necessitates a reducing member from the motor. Belts are precluded, but motors may be connected through a suitable clutch or coupling to the high-speed member of a chain or gear reduction. I am inclined to favor a flexible coupling on the motor shaft in combination with a suitable drum to which a mechanical brake may be applied. This avoids one piece of apparatus, subject to repair or inspection, and the brake effects a safety device for quick stopping. The use of chain or gears is optional. The chain, no doubt, has a good point in relieving the pinion shaft of heavy impact, but it will probably exceed the gears in first cost and space occupied. The gears, if used, should be in a self-contained unit, held in rigid alignment, and operating in oil. I mention these mechanical features as the satisfactory operation of the motor depends largely on the proper design and installation of the driven machinery.

6. *Load Conditions*. I have previously stated that individual drives should be avoided. The method of operating mills is such that the load is variable in the extreme, and machines should be grouped to take advantage of the diversity factor. Figures will illustrate this effect. A 22-inch by 60-inch mill for individual drive will require, in most cases, a 100-h.p. motor, but when grouping these mills, we can readily reduce the total average consumption of a mill to from 55 to 65 h.p. The average graph from a group of mills will show a minimum load of 50 per cent of the average, and peaks of from 150 to 175 per cent of the average. These figures are merely illustrative. The peaks are apt to be prolonged, and must, therefore, be provided for in pull-out torque design. Their heating effect is inconsiderable. The use of a flywheel may be of decided advantage in some cases, but it is not generally used. I believe its general adoption might be advantageous.

7. *Starting Conditions*. The cumbersome design of the machines in question is such as to effect an extreme condition in starting. This is especially true after periods of shut-down, when the lubricants become more or less disseminated. Mill motors are not started frequently, but provision must be made for quick stopping of the machines, reversal of the motor, and starting the machines again in the opposite direction. This brings up again my line of argument in favor of phase-wound motors, mechanically connected to the driving unit with a flexible coupling. It is obvious that this unit can be disconnected from the line, mechanically braked, phases reversed, and started, in much less time than a motor which is

clutch-connected, and must be disconnected from the line by hand and the momentum allowed to decrease before reversing and starting up. Furthermore, the latter motor must be up to speed before the line is actually reversed, by throwing in the clutch. As a safety precaution, moments count, as the heat of the rolls is very harmful to the operator, who may be caught, and in fact, it is apt to cause more trouble than the crushing.

8. *Speed.* The low speed of the line shaft is such as to have led the engineers to adopt motors whose synchronous speed has, as a rule, not been over 600 revolutions per minute. The size of motors usually employed at this speed is such as to insure rigid construction, usually with pedestal bearings; vibration is a minimum, and speed reduction on the order of 6 to 1. Moreover, it is my opinion that the increased diameter of the low-speed rotor, together with its weight, gives more flywheel effect than the higher speed rotor, with decreased weight and diameter. I have no figures at hand which substantiate this, however, it can be easily checked.

9. *Control.* The control will differ with the type of motor, but several features are obviously required. No automatic controls are necessary, and would only require a comparatively high investment and upkeep. The starting equipments must be as near fool-proof as possible, as they are to be operated by inexperienced employees. The primary switch should in all cases include no-voltage release, and inverse time limit relays. The former is connected to the safety bar over the mills by a suitable means, as is also the tripping mechanism for the brake or clutch. Phase reversal is accomplished by means of a knife or oil switch, conveniently located near the starting apparatus.

10. *Conditions of Location.* Conditions surrounding the motors in the plant are not of the best. The principal troubles are occasioned by two things: the chemical union of the sulphur dust with exposed copper, and the clogging action of the dust, which penetrates the most obscure places. These two conditions suggest the following precautions: to avoid the exposed contact, and provide dust-proof bearings. Here again, the engineer's personal decision leads him to adopt the lesser of two evils. I believe in the judicious use of exposed contacts, as they are superior to oil-break switches for use in starting large motors. I refer particularly to primary and secondary starting apparatus for slip-ring induction motors. The dust acts in several ways, to clog oil rings, to gather in windings, and prevent heat dissemination, due to the high specific heat of the soapstone, to bind brushes in holders, and to prevent cam and plunger action on circuit breakers, etc. These troubles are obviated by inspections, and the careful use of air blowing.

I will attempt to summarize briefly the main points to be considered in the design of a mill drive. Avoid the use of direct current. Group mills in units of from four to eight. Provide flexible couplings between reducing member and main shaft and install a reducing member of liberal proportions, self-contained, with bearings accurate, and rigidly aligned. Install the most efficient coupling between the driven member and the motor which can be obtained. Avoid the arbitrary use of the horse power per inch of roll rule, which may be misleading. No blanket rules are available for horse power consumption. Provide means of disconnecting motor for starting if of the squirrel cage type, or use slip-ring motor if direct-connected through coupling. Starting equipment should include overload and no-voltage releases, together with inverse time limit relays, the former being operated by the safety bar of the mill.

I will now present the several conditions affecting the design of calender drives.

It is practically true that all rubber stocks not being used in molded goods or tube machines are calendered. Except in cases where impressions are to be made, the rolls are ground smooth, slightly crowned to provide for spring, and with an adjustment which allows the operator to gage the product with an accuracy of less than the one-thousandth part of an inch. Low speed in calender work is necessary during the threading-in process, and until the gage is accurately established, after which, economy dictates as high a speed as the stock will permit. This speed is limited by the heat generated, which affects the physical and chemical characteristics of the rubber base and ingredients of the compound. Slight variations in speed affect the gage materially, hence good regulation is of prime importance. The torque required varies with the width, thickness and kind of stock being treated, while the horse power required varies approximately with the speed. The torque and speed, however, are so inter-related that the resulting horse powers are not of as extreme variation as might be expected. The usual maximum is about four times the minimum; this statement referring both to operating speeds and horse powers.

From an analysis of the previous description, it will be seen that variable-speed motors are of unquestionable value, also that the degree of variation depends entirely upon the class of goods worked. Hence, plants differ widely in their calender motor requirements.

Value of a calender drive, as in all industrial applications, is a function of production. This involves a fine degree of speed control, good regulation, convenience of manipulation, and continuity of service. Fine speed control results in careful threading-in and later enables the operator to work the stocks to the limit in speed, under which speed, labor is inefficient, and over which, stock may be spoiled. Good regulation results in pre-determined gage, and this, in turn, in economical production, as all rubber of heavy gage is lost in vulcanization, and must be reclaimed. Continuity of service affects the smaller plants principally, where daily output may be confined to a few machines. The use of direct-current motors undoubtedly combines in a greater degree the advantages above enumerated than any alternating-current system of practical application.

I will now touch upon the points tabulated by Mr. Rushmore with reference to motor drive for calenders.

1. *Alternating or Direct Current Available?* Both alternating, and direct-current drives are in use in rubber plants and both have their advantages. Assuming an alternating-current supply, in a plant producing mechanical goods of a comparatively low grade stock, it is unquestionably correct to install a multi-speed induction motor, possibly in conjunction with a two-speed gear unit, and clutch, thereby avoiding the losses, complications and investment of the more comprehensive direct-current system. The stocks referred to as mechanical are usually worked with low speeds, and do not differ materially in characteristics, so that the engineer can readily find four speeds which will provide all that is desired in the way of maximum production. I am firmly convinced, however, that the conditions as outlined are the only ones which warrant the use of an alternating-current drive.

Recent installations have been made including squirrel cage induction motors with multipolar windings, and provisions for changing the frequency of the system which result in from four to six distinct speeds. Aside from engineering complications in design of automatic switch operation, I believe that the successful running of the calender for maximum product is seriously handicapped. The maximum speed at which a stock may be run may fall between two speeds available, and as the stock must be worked at the lower speed, machine efficiency may readily be on the order of 80 or 90 per cent. I will omit further discussion of alternating-current systems, and continue my subject matter, assuming a direct-current supply, preferably the three-wire, 110–220-volt system.

3. *Capacity of Generating Station and Line.* The variable nature of the calender load necessitates the use of time limit relays in order to obtain an average load approximating that of the generating equipment. A generator of say five hundred kw. capacity may readily have peaks of over 750 kw. impressed upon it for short periods, while the average load may be fluctuating around 300 kw. Hence the use of the relay.

4. *Description of Machine, etc.* Calender motors, should, I believe, be rated for continuous service, but standard heat guarantees will suffice. The work is more or less intermittent, to be sure, but the periods of stop are short, and in many cases negligible. Machines cannot be handled to avoid simultaneous operation, but with the three-wire system, machines on the same class of work are staggered with reference to their start-

ing connections, and a remarkable balance is thus effected. On a three-wire system with which I am familiar, unbalance has never exceeded 30 to 40 per cent of neutral line capacity, and is usually very slight.

5. *Method of Drive.* Individual drive is a necessity today, following the use of the motor, although some of the smaller plants operate from line shafts driven at constant speed. The usual installation today includes the motor rigidly constructed for mill service, which may be connected to a flexible coupling or clutch and to the speed-reducing member of the calender. Here, as in the mill drive, mechanical design is of prime importance, and all vibration should be provided against. The use of the clutch provides adequate means for insuring a quick stop, while the engineer adopting the flexible coupling must provide dynamic braking devices on the control panels.

6. *Load Conditions.* There are several salient variables affecting the load conditions of the calender: size of machine, speed, gage and specific gravity of stock being among the most important. It will, therefore, be seen that rules for motor sizes are special in every case. There is a more or less definite cycle duty, but it will not modify my previous statement for a motor designed for continuous duty. Variations in load can readily be effected by change of the variables just mentioned, and the engineer must entrench himself by making actual tests of conditions, if possible. The usual limits may be found by power consumption readings taken while running on high gravity, low speed, heavy gage stocks, and again on high speed fabric frictioning. Flywheel effect is desirable only in certain cases where passes of stock are made which are comparable to rolling mill practise. These applications are few in number.

7. *Starting Conditions.* Calender drive should certainly provide convenient and ready means for starting and stopping. A floating stop is all that is necessary in the ordinary run, but in case stock or fabric wrinkles, or the operator becomes caught, the connecting clutch or dynamic brake switch must be so connected as to provide instantaneous stop. Starting conditions are quite severe, and assuming the use of the shunt-wound motor, it is desirable to specifiy several turns of series field winding to improve the torque at this period. Shut-downs may occur frequently with a mass of rubber being worked, hence it is desirable to back the machine up to avoid heavy starting current. An armature reversal switch is indispensable.

8. *Speed.* The subject of speed has been touched upon. Close regulation is not only desirable but necessary; this purely from the standpoint that it permits of an accurate gage. The questions of multi- or adjustable-speed drive is mooted. Maximum production at lowest labor costs, and inherent stock conditions are certainly to be considered, and I believe conspire against the use of the multi-speed drive, except in the one case

noted in a previous paragraph. The speed range is limited by well established lines, these lines being local, however, for each plant. The minimum speed is determined by the maximum speed at which the operators can handle starting of the process, and the maximum speed is limited by the heat-resisting qualities of the stock, and by mechanical limitations. This range is, I believe, never over four to one, and should not be less than three to one. Economy dictates the use of a field weakening motor of proper design to give a reduction in speed of two to one, the total range being passed through by connecting the armature to two or more voltages in sequence. A compromise should be effected in multi-speed between first cost of motor and maintenance. By this I mean, the use of as high a speed driving unit as can be utilized without encountering difficulties in maintenance occasioned by vibration, excessive wear of gears, etc. Experience has shown that motors should probably not exceed seven hundred and fifty to eight hundred rev. per min.

9. *Control.* The engineer and manufacturer will be amply repaid by installing the most complete full magnetic control board obtainable. The process is speeded up, the operator is unable to harm apparatus by improper manipulation, and efficiency is promoted to the finest degree. The usual installation of this kind includes overload and no-voltage release relays and if necessary dynamic braking is accomplished by proper means. The controller is conveniently located on the calender housing, and safety bars pass the points of danger to the operator.

10. *Conditions of Location.* The use of direct-current drives with the consequent exposed copper surfaces is a necessary evil. The action of the sulphur and fumes is such as to coat the copper with a high-resistance sulphide which is very troublesome, particularly on low-voltage relays. Soapstone dust acts as noted in my previous paragraph on mill motors. The time required for these bugbears to become evident by faulty operation of panels is short and hence constant supervision becomes almost necessary. I have found it economical to provide constant attention to direct-current apparatus, as such a step has resulted in reducing electrical trouble to a negligible quantity and at the same time cutting maintenance costs.

The more essential points touching the calender drive may be summarized in the following:

1. Provide a direct-current supply, insuring minimum losses to system as a whole.

2. Potential of system should be as low as good engineering will permit. This insures the operation of the magnetic switches without undue flashing.

3. Secure load-speed tests under conditions of maximum load, and minimum speed, and vice versa.

4. Restrict motor speeds for mechanical reasons. Install the highest developed full-automatic control panel obtainable,

together with all mechanical provisions possible, working for rigidity, elimination of vibration, etc.

5. After installation, insure satisfaction by frequent inspections and adjustments, to keep the system in the best of repair.

Friction Drive

C. W. Larson: Friction as a means for drive is practically eliminated in modern power requirements. This is entirely due to the successful application of electric motors to all kinds of operations and they are nearly always connected direct to the member or members to be driven. There are, however, occasions where drive by means of friction is necessary as no other method has as yet been developed to take its place. Such a case was involved in the design of the Panama towing locomotives.

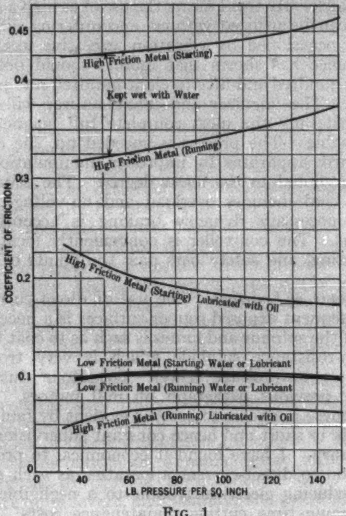

Fig. 1

It was required that a slip device be provided to safeguard the tow line from parting should the strain exceed a certain maximum. It was also necessary that this slip device be set at different values from zero up to full capacity of the motors and not vary in friction over 5 per cent. It will therefore be seen that if the friction method was to be used, a combination of material must be found that would maintain a constant coefficient of friction under all conditions, including starting from rest and running.

It was immediately realized that a metal or combination of metals had to be found that would give the least possible friction. In conducting a series of tests using different combination of metals, it was found that high friction metal would be out of the question. An alloy was finally selected having a coefficient of friction of 0.1. The results of the tests are shown in Fig. 1, from which it will be noted that the coefficient of friction of 0.1 remained practically constant, starting and running, whether the surfaces were lubricated or run in water. I wish, however, to point out that the design must be such as to completely carry off the heat, as a great variation in temperature will upset the mechanical construction and consequently also affect the friction. It will therefore be understood that the design must be made to conform to the different conditions as they may present themselves in each individual case.

Explosion-Proof Motors for Use in Gaseous Mines

The term explosion-proof as applied to motors for mine work, according to the definition of the Bureau of Mines, refers to a motor enclosed by a casing, so constructed that an explosion of a mixture of mine gas (methane) within the motor casing will not be communicated to the gases surrounding the motor. That is, it will not cause an explosion of the mine gases.

Explosion-proof motors can be considered of two classes: First, a totally enclosed class, built strong enough to withstand a high internal pressure, and so designed that the covers on the necessary openings can be satisfactorily maintained. Second, a class provided with relief openings or valves, designed to relieve the internal pressure of the explosion and at the same time cool the products of combustion discharged through them to a temperature that will not ignite the mine gases.

To build a motor of the first class would be much more expensive than to construct one of the second class. For this reason attempts to design explosion-proof motors have been confined chiefly to motors of the second class. That is to say, the designers have largely followed the principle involved in the Davy safety lamp. The application of this principle to motors consists in causing the discharged gases to pass over or through metallic plates, screens or valves, which by conduction remove a large part of the heat from the gases. For the sake of simplicity, these devices whether they consist of valves, layers of glazed metallic plates or any combination of them are termed protective devices.

As the ignition temperature of mine gas (or methane) is 650 deg. cent., it is evident that an explosion-proof motor to be successful, should discharge the products of an internal explosion reduced in temperature below this figure.

In a successful explosion-proof motor, particular attention must be given to the design of the protective devices. The most satisfactory form of protective device is one that is capable of absorbing a large amount of heat. In order to do this, the device should be constructed of metal that is a good conductor of heat. A considerable amount of metal should be used and it should be so disposed as to offer a large amount of heat absorbing surface to the flames without being itself raised to an unsafe temperature. The total area of protected openings from the wall of the motor case, should be as large as is consistent mechanically. There are two reasons for this arrangement. First, it permits the addition of more heat absorbing material; second, it decreases the maximum pressure developed. The lower the pressure, the lower the temperature of the flame and the less heat is passed through the cooling device in a given time. With low pressure, the rate of combustion is slower, consequently, heat absorption is facilitated.

An explosion-proof motor of the second class has been designed and has been tested and approved by the Bureau of Mines for use in gaseous mines.

MOTOR INSTALLATIONS FROM A SAFETY AND INSURANCE POINT OF VIEW

C. A. Austrom: The application of motors in industrial plants has already been very thoroughly discussed from a technical and economic viewpoint. It remains to be considered what influence motor drive—whether individual or group drive—has from a safety and sanitary point of view and in what way it would affect insurance.

In the past, the appeal made to the manufacturers by the electrical interests has generally been on an efficiency and cost basis only, and the manufacturers of electric motors have continually been investigating and experimenting in an effort to produce a machine which will do more work at less cost.

The advocates of shaft drive for industrial machines have also been engaged in a similar effort to meet the competition. Neither side has until lately given much thought to the question of safety and as to which system is the least dangerous for the workmen.

Accidents which are directly chargeable to the type of driving mechanism add a certain cost item to that system in the form of interruption in production, suits for damages due to accidents, compensation charges and higher insurance rates. These items should be well considered when a comparison between shaft drive and motor drive is made. The greater safety to the workmen and improved sanitation cannot any longer be considered as a side issue, but should be a strong argument by the manufacturers in selling their machines.

In a modern plant we do not find, as was often the case in the past, the haphazard method of laying out the machines on the floor of the factory or the shop. Efficiency and safety are rapidly becoming more and more important and great attention is given to the location of the machines in regard to the handling of the product, the light, ventilation and safety of the workmen.

The old, and still greatly used, method of driving machines from main shafting and countershafting is a source of danger which has caused many accidents and claimed a heavy toll in life and limb of the workers. A large percentage of fatal and serious accidents in industrial plants is due to this countershafting with its pulleys, belts, keys, collars and more or less exposed set screws. The statistics of insurance companies show that a great number of men have lost their lives or have been permanently maimed by being caught by exposed set-screws or crushed between belts and pulleys. There are many cases where women's hair has been caught and wound around perfectly smooth shafts with fatal results.

Shaft-driven machines are generally started by means of a tread or a lever which shifts a belt or operates a clutch. On machines like punch presses and shears, accidents have often happened by these operating devices being touched unintentionally, thus starting the machine and seriously injuring a man engaged in setting dies or adjusting shear blades. Another way by which the machines may be started unexpectedly is, for instance, a gradual creep of the belt from the loose to the fixed pulley, in this way suddenly starting the machine at full speed. The main shaft may be stopped for some reason or other and started up without due warning to the man, who may in this way be seriously injured. With individual motor drive, the starting switch can easily be located in such a way that an accidental starting of the machine would be impossible. All accidents of the nature referred to above could be eliminated if shaft driven machines were abolished in favor of motor driven machines.

It may be claimed that shafting can be guarded more or less efficiently, but accidents will occur even with the best protection, and it is safest to entirely eliminate shafts and belts.

Shafting and countershafting are usually located along the ceilings, and bearings, pulleys and other accessories can only be reached by ladders. These various parts require frequent and regular attention for oiling, inspection, etc., and sometimes even repair work is carried out while the shaft is running. The regular attendants and repair men have often to work on these ladders in crowded and cramped positions and many serious accidents have happened under these conditions. Of course, repair work should never be permitted when the shaft is running; but even though the shaft is stopped, the work from a ladder is always hazardous, and any scaffolding erected for the purpose is generally put up in a hurry and in a flimsy way, making it more or less insecure and dangerous to the millwrights working upon it. Parts of a transmission line fixed in the ceiling may work loose and be a source of danger by falling on the men below.

Accident records also show many cases where men's fingers and hands have been seriously cut by running belts, particularly where the same are jointed by clips, and numerous accidents have occurred from the men's clothing being caught in the same way. This danger is particularly great where the practise of belt shifting by hand is permitted.

Shafting, pulleys and belts make it difficult and dangerous to handle material by cranes or overhead runways, and accidents have often happened from such operations. This hazard is entirely eliminated where direct, individual motor drive is used, particularly if all wiring is run through conduits under the floors so that there is no obstruction whatever above the machines and in the passageways between the same.

Belts, shafts, bearing hangers and other accessories pertaining to shaft drive cut off a considerable amount of light around the machines, making it necessary often to use artificial illumination even during the day hours. With individual motor drive these obstructions are eliminated and the light in the room equipped with individually driven machines is naturally far better than in rooms with shaft-driven machinery. The belts not only intercept the direct light from the windows, but the ceiling is often made dark and dirty from dust and oil thrown off by belts and pulleys. The hangers and pulleys are generally themselves of a dark color, so that there is very little light reflected upon the machines from above.

In a shaft-driven installation, the machines must be arranged in parallel lines, generally lengthwise of the building, and in order to economize floor space often have to be placed back to back, so that half of the men work in their own shadows while the other half face the light. Either of these conditions is trying to the eyes, and in the long run tires the men and impairs their sight. At the same time it is obvious that such conditions also tend to reduce the output very materially. When the machines must be placed in fixed positions in relation to the shafting and without regard to the direction of the light, and the operator consequently has to work in a darkened room or with continuous artificial light, the likelihood of accidents is greatly increased. The contrast in these respects that is afforded by factories operated by individual motors is quite striking. When so equipped, machines can be located properly, with due reference to the best light and the safest arrangement as to floor space. It is also more easy to avoid crowding, an important factor in preventing accidents.

When each machine is driven by its individual direct-connected motor, making one self-contained unit, it is very easy for the manufacturers of such machines to embody in the design all the necessary guards for gears or other dangerous points. When the machine is purchased it carries with it all necessary safeguards or devices to prevent accidents to the men operating the same, and no further expenditure will be required to make the plant safe after such machines are once installed.

It is easy to understand that a factory equipped with machines individually motor-driven can be kept in a much neater and cleaner condition than a room filled with shafts and belting. Consequently the sanitary conditions are all in the favor of the motor drive.

The safest installation that can be obtained is where all machines are driven by direct-connected individual motors. Any machine can be readily stopped and is under the complete control of the operator of that machine. This eliminates the danger which has so often occurred in the past, of inadvertently starting the machinery when some machine was being repaired by its operator.

The next best condition is where the machines are driven in groups of a small number of machines to the group. Naturally this brings up the question of introducing the hazard of belts and pulleys, but by keeping the number of machines in the group to a maximum of say, ten, the danger of injuring the workmen by starting up the machinery through carelessness is eliminated to a great extent. Such a small group can be easily controlled in such a way that accidents are not likely to occur.

In the old type of plant the machines in one room, or department, are generally belt-driven from the main shaft, which usually can only be stopped by shutting down the entire plant. The only way in which such an installation can be safeguarded is by having some method of stopping all the machinery in each room or department by means of a friction clutch or other standard device, or by having each such group of machines driven by a motor. In this manner, if anything goes wrong in one department no time is lost through having to communicate with the engineer or the operator of the main engine and shafting, but each individual group can be separately and immediately shut down by a man working in that room. This method of driving machines is, however, not much better than running the machines from the main shafting, but there is a small distinction made as regards the insurance rates, the so-called department drive being considered somewhat safer.

In addition to the factors of safety referred to above in connection with motor-driven plants, the insurance interests have taken due notice of the improved conditions from an underwriting point of view, which follow the adoption of motor applications. The safe and dangerous conditions enumerated above have been carefully considered by the Workmen's Compensation Service Bureau in its Universal Analytic Schedule. This is adopted by all leading insurance companies, and credits or charges are made in accordance with the type of drive used for industrial machines. The various types of installation are taken up specifically in this schedule and can best be illustrated by giving an example. Taking a machine shop having, say, twenty-five machines and an annual payroll of $50,000, the compensation rate for such a machine shop in the State of New York is at present $1.36 for every $100 of payroll. The total premium in this plant would, therefore, be 500 by $1.36, or $680. Now suppose each one of these machines is driven by a direct-connected individual motor, for which the Universal Schedule allows a credit of 10 per cent of the base rate—in other words, 10 per cent of the premium. In this case, therefore, such an installation would give the owner a reduction in his insurance premium of $68.00 per annum.

If, on the other hand, machines are driven in groups of not more than ten machines to each group, the schedule allows a credit of 7 per cent, which would mean a saving to the assured of $47.60 on his annual insurance premium.

If in such a plant the machines are driven by departments, with proper means of disconnecting all the machines in each department from the main shaft by means of a clutch or other device, or if each department shaft is driven by its own motor, the credit allowed would be in proportion to the payroll of the plant. The amount allowed approximating ten so-called points per department, the value of the point depending upon the payroll of the plant. In this case, if all the twenty-five machines were in one group, the amount would be $2.50. If they were divided into two departmental groups of, say, twelve machines in one and thirteen in the other, the amount would be $5.00. This credit seems very small, but in comparison with the two previously mentioned types of installation, this last is considered far more hazardous by the insurance underwriters.

The examples given above are in accordance with the rates at present in force in the state of New York. These rates vary somewhat in different states, depending upon local legislations. If the state laws in the future are made more or less similar, as, for instance, is the case in the rules and regulations for steam boilers, the insurance rates will be adjusted accordingly, so as to be universal for the whole country. The schedule Rating System as introduced by the Compensation Bureau seems at present to work to the satisfaction of both the assured and insurance companies.

From what has been said above, it is evident that motor applications in industrial installations, particularly the individual motor equipment for each machine, is the ideal arrangement from a safety, sanitary and insurance point of view.

Explosion-Proof Apparatus

W. Baum: The application of electricity in fiery mines has attracted the attention of the engineering professions for a great number of years. Our present knowledge of the underlying principles and phenomena in connection with fire-damp explosions is due to the ingenious and painstaking experiments made abroad and in this country and to the close co-operation of mining and electrical engineers.

The best precaution in the application of electricity in fiery mines is to install the apparatus at points where fresh air can be supplied. Large pumping motors have been installed in special air-tight chambers which prevent the entrance of gaseous mixtures. Such chambers are recommended for the installation of large motors which do not permit the use of special protecting devices.

Hoisting machines are placed at the lower end close to the opening-up shaft and with this arrangement the apparatus can be placed in a current of fresh air and avoid the presence of fire-damp which always accumulates at the highest points of the workings on account of its small specific weight (0.554).

However, the above-mentioned arrangements are not always possible, as fresh air ventilation often cannot be obtained. The problem arises to provide electrical apparatus with some sort of a protection which prevents puncture. In other words, if an explosion takes place in the interior of an electrical apparatus, a protective device must be employed which prevents the ignition of the surrounding gases.

The classical experiments carried out conjointly by the leading German electrical firms and the mine authorities in 1903, 1904 and 1905 have remained the basis for the design of such protecting devices. The practical results of these tests have been verified in other countries and our knowledge and understanding of the explosion characteristics has increased to such an extent that any opposition to the installation of electrical apparatus in fiery mines can be effectively met. Credit is also due to the investigations of the U. S. Bureau of Mines.

Fire-damp is a mixture of air and methane, CH_4. Other gases have been detected, for instance, ethane, free hydrogen, the noble gas helium and others. The explosion temperature of methane is 650 deg. cent. but according to English and French investigators, explosions must be anticipated at lower temperatures when ethane or other gases are present. It is, however, doubtful whether these gases will seriously affect the results of the original experiments. Theoretically, the maximum explosion pressure occurs with a mixture containing 9.5 per cent methane. Recent experiments in France have shown that the most violent explosion corresponds to the maximum velocity of propagation of inflammation. The German and American experimenters observed the maximum explosion pressure with 8 per cent and 8.6 per cent respectively.

The fundamental experiments in Germany resulted in three forms of constructions which have proved successful in the design of explosion-proof apparatus, namely:

1. Total enclosure.
2. Laminated plate protection.
3. Oil protection.

Other constructions as labyrinth, flange, tube and gauze protection are very interesting but of no practical importance with the exception, perhaps, of the latter. This gauze protection, however, has the dangerous disadvantage of after-burning.

1. *Total Enclosure.* The apparatus is totally enclosed and made as air-tight as possible. The casings are designed to withstand the maximum explosion pressure of eight atmospheres. This type is favored in Germany by one of the large manufacturers, and for obvious reasons can be applied to small motors only. Large motors are often provided with air or water cooling features to maintain a minimum weight. These special features, of course, complicate the operation and lead to higher costs.

2. *Laminated Plate Protection:* The principle of this device is based on the Davy lamp screen which breaks up the gases into small streams and permits effective cooling. The device consists of laminated plates fixed to the end openings or to the covers of the apparatus through which the gases travel and expand, thereby securing an additional cooling effect. The statement that the plate protection has given the best practical results, must be emphasized. The important condition is, however, that the plates must not exceed a distance of ½ mm. (0.0197 inches) and any deviation from this condition results in punctures as also shown in the experiments of the U. S. Bureau of Mines. As a rule, the plates are ½ mm. (0.0197 inches) thick and are suitably protected against injuries from falling pieces. If the openings are not frequently and periodically cleaned, coal dust will accumulate and seriously interfere with the ventilation. In case of an internal explosion, the coal dust will simply be blown out without igniting. The plates are often arranged in a frame to facilitate removal, cleaning and replacement. A sufficient number of plates must be provided to secure satisfactory cross-sectional flow of air through the plates and with properly designed construction the reduction of output will be nearly the same as that due to alteration from an open type motor to a ventilated enclosed motor. An artificial increase of ventilation by means of a fan should be omitted as the internal pressure is raised considerably, according to the experiments of the Bureau of Mines.

3. *Oil Protection:* Switches, controllers and other accessories in fiery mines must be explosion-proof and are to be protected against moisture, dirt and unskilled handling.

A German company has developed controllers up to 5000 volts in which the contacts are completely covered by oil to prohibit the formation of arcs. The oil tank can be lowered by a special mechanism, thus permitting free access to the contacts. The same company has designed oil switches with maximum and no-voltage release placed in cast-iron cases and submerged in oil. For underground lighting, oil switches are built on top of transformers, thus forming a unit. The oil switches can be provided with plate protection and in such a case, there is no need of submerging the overload coil in oil. Whenever oil protection is used, it must be borne in mind that the current densities of the contacts must be low enough to prevent heating of the metal parts, vaporization and decomposition of the oil. Of course, all contacts, must be completely covered by the oil, as otherwise flames may break through and cause ignition. The contacts should, therefore, be placed at the bottom of a tank of sturdy construction.

New protective devices by German firms are usually submitted to the mining authorities for tests and with their approval are put in standard production. Before shipping, however, each apparatus is tested in a trial station which each of the leading firms has provided for the purpose of testing explosion-proof apparatus. While the mining authorities use fire-damp obtained from a mine, the factory tests are taken with a mixture of air and approximately 15 per cent illuminating gas. These tests do not claim scientific importance as the nature of the explosions with illuminating gas are somewhat different from those with methane, but for the purpose of detecting undesirable gaps or other faults, they are entirely satisfactory.

It is interesting to note that a great many years ago standards on the application of electricity in mines were adopted in foreign countries: in Belgium 1895, in Austria 1899, in England 1902 and in Germany 1903. The latest standards covering the design of explosion-proof apparatus were adopted in 1912 by the German Society of Electrical Engineers (V. D. E.). As these exhaustive rules have done much to encourage and stimulate the design of such apparatus, I wish to read an English abstract translation for the benefit of those who are not already acquainted with them.

REGULATIONS FOR THE CONSTRUCTION OF EXPLOSION-PROTECTING DEVICES FOR ELECTRICAL MACHINES, TRANSFORMERS AND OTHER APPARATUS

A. The Different Kinds of Protection Devices:

I—Enclosed Casings: It consists of a totally enclosed casing covering machines, transformers and other apparatus. For this enclosure the following requirements are to be met:

(a) All parts of the casing are to be so constructed that they can withstand an inner pressure of eight atmospheres (113.6 lb. per sq. in). Subdivisions of the enclosed interior inter-connected by narrow openings give rise to higher pressures and should, therefore, be avoided.

(b) The joints of the assembled enclosed parts as well as the bearing surfaces of covers, doors and lids are to be broad, smoothly machined flanges. Gaskets at such places should be avoided as far as possible. In case gaskets are used, care should be taken that they cannot be forced out by explosions. Gaskets made of material subject to deterioration, as rubber, asbestos, or the like are not permitted.

(c) The protecting means are to be extended to all passages through which the gases, in case of an explosion, escape from the interior of the casing to the outside. Shafts and operating spindles are to be supported in long metal bushings where they pass through the enclosing case and these bushings themselves are to be securely fastened to the casing.

The bushings for electric wires are to be tightly packed in such a way that they will withstand the pressure of an explosion.

II—Plate Protection: With this type of enclosure, packets of metal parts are mounted at the openings of the housing of machines, transformers and other apparatus. The plates are held at a definite distance apart by means of separating pieces.

The following rules are to be observed:

(a) Metal plates are used which have a width of at least 50 mm. (1.97 inches) and a thickness of at least 0.5 mm. (0.0197 inches) and are arranged by means of suitable separating pieces so that their distance apart does not exceed 0.5 mm. (0.0197 inches) and cannot be exceeded on account of bending of the plates. The material used is to be bronze, brass, tinned or galvanized iron.

(b) The plate packets are to be protected against outside injuries. It is recommended to make them removable so that convenient inspection and easy replacement are possible.

(c) The conditions under *I*(b) and *I*(c) are to be met. Unless the number of slits is not sufficiently large to prevent a rise of pressure, the conditions of *I* (a) are also to be met. All parts are to be perfectly tight.

III.—Wire-Gauze Protection: In this method of enclosure all housings of machines, transformers and other apparatus are covered by screens of wire gauze, or housings are constructed for machines, transformers and other apparatus in which openings are covered by such wire gauze.

The specifications for this enclosure are the following:

(a) The gauze is to be made of safety-lamp wire gauze of 144 meshes per sq. cm. and 0.35 mm. wire diameter (930 meshes per sq. in. and 0.0138 inches wire diameter). The wire gauze is to consist of bronze or galvanized iron, to have uniform structure and be free of defects.

(b) Each opening is to be provided with at least two layers of wire gauze which should be spaced 5 to 20 mm. apart (0.197 inches—0.79 inches). The total protection gauze surface is to be at least 150 sq. cm. per liter of fire-damp contained in the enclosed space (approximately 21 sq. in. per 1 quart).

(c) Large gauze surfaces are to be provided with strengthening ribs in order to maintain their distance apart. The gauze is not to be secured by solder but rather clamped in frames by means of screws. Great care is to be taken that no gaps occur at the points of fastening. The gauze is to be protected against injury by perforated iron or similar means. It is recommended to arrange the gauze in removable covers to permit easy inspection and replacement.

(d) The conditions of *I*(b) and *I*(c) are to be met. All parts are to be perfectly tight.

(e) The gauze surfaces are to be so arranged on the enclosed case that flames due to any after-burning do not travel along the gauze and that combustible bodies cannot fall upon them. In order to decrease the after-burning many small surfaces rather than few large ones are to be used.

IV.—Oil Protection: In this method of protection the whole apparatus which is liable to sparking or dangerous heating due to the electric current is enclosed in a casing filled with mineral oil free of resin and acid. The oil level is to be so high that sparking above the level is impossible. The required height of the oil is to be indicated by a mark. The height of the oil is to be visible without opening the case.

B. Application of the Various Protecting Devices:

I. For machines, transformers and other apparatus, two kinds of construction may be used:

(a) The entire machine, transformer and apparatus are to be made explosion-proof according to section *A*.

(b) Only those parts of machines, transformers and apparatus which are liable to sparking in ordinary operation, are to be made explosion-proof according to section *A*. The safety of those parts, however, which are liable to sparking only under unusual conditions is increased by

1. A special mechanical inspection.
2. 50 per cent increase of insulation stress.
3. 25 per cent decrease of heating guarantees.

For apparatus other than machines and transformers the following applies:

Liquid starters without special protection are not permitted.

Rheostats may be furnished without protecting devices under the following conditions:

(a) The electrical stress of the material is so small that dangerous heating is impossible.

(b) The resistance material is so strong that it cannot break in normal operation and is so securely fastened that contact between different parts is prevented.

(c) By proper enclosing, foreign bodies cannot fall in, and dripping water cannot enter.

(d) All wire connections are soldered or securely screwed together.

All screw contacts which cannot be protected by enclosures, should be so secured that a loosening of the screws and a resultant poor contact cannot take place (motor terminals, resistances, etc.).

Plug contacts are to be so constructed that the plugs fit tightly in the receptacle and thus prevent sparking when in place; they are to be inter-locked with explosion-proof switches in such a way that the plugs can only be set in or taken out when the circuit is open.

C. Other Constructions.

Other constructions than those mentioned under *A* and *B* for protecting machines, transformers and other apparatus are permitted if such devices have been found to be explosion-proof by a special test at a recognized station for explosion tests.

We see from the last paragraph of these regulations that the various constructions mentioned are not considered to be the only ones possible to devise. But the German rules show the direction along which the design of explosion-proof apparatus should be followed and it is to be hoped that the tests carried out in this country by the Bureau of Mines will ultimately result in the adoption of similar rules by the American Institute of Electrical Engineers.

THE INFLUENCE OF INFLAMMABLE MINE GAS UPON THE DESIGN OF MOTORS FOR MINE SERVICE

H. H. Clark: Methane (CH_4) is an inflammable gas that occurs in many coal mines, especially the deeper ones. The mine ventilating systems are designed to remove from the workings the gas that escapes from the coal and to remove it in a condition so diluted with air that it cannot become ignited.

Electrical equipment should not be used in mines or parts of mines where the proportion of ventilating air to the gas that it carries away is not so great that the presence of explosive mixtures is the rare exception and not the general rule. However, since the gas enter the workings at a very ununiform rate and at the more remote points in the mine where the ventilation current is least strong, the gas, although usually removed promptly, may sometimes accumulate in dangerous quantities in caved areas through which there may be very little ventilation. This condition may also occur at the face of a working as the result of an interruption or disarrangement of the ventilating system.

These possible accumulations of gas or the occurrence of a large blower of gas at the face constitute the danger against which the use of explosion-proof protection of electrical equipment can consistently be used.

The U. S. Bureau of Mines has applied the term " explosion-proof " to motors or other pieces of electrical equipment that are so constructed or protected that they will not cause the ignition of explosive mixtures of mine gas and air. Various similar terms were considered before this term was finally adopted as most expressive and fitting, as well as the term used exclusively by the original German investigator, to whom the art is largely indebted.

The use of explosion-proof protection should be regarded as a factor of safety in emergencies and not as the principal bulwark against the ignition of gas by electrical apparatus. The ventilating system must always be regarded as the main defence against such contingencies.

Motors that Require Protection. The motors that most need explosion-proof protection are those that are to be used in the advance workings. The most notable examples of such motors are those used for operating coal cutting equipments. In mines that produce a good deal of gas, motors that are operating on the return air-way might also with reason be provided with explosion-proof protection.

Motor Parts that Require Protection. The commutator of direct-current motors is the first thing that suggests itself as needing protection when one considers the subject of explosion-proofing, but it is manifest that any part of a motor equipment that will produce a spark capable of igniting gas must be protected as completely as the commutator.

Dangerous sparks can be produced at the contacts of starting rheostats and wherever the circuit is intentionally broken automatically or by hand or wherever the circuit may be broken accidentally. It is common experience that portable machines are subject to breaking of wires that connect one part of the motor to another. Therefore, it is desirable to protect all wires so that the possibility of their being broken is reduced to a minimum, and it is best to design the equipment so that all wires are in explosion-proof casings from the point where they enter the machine. Therefore, to be specific, the entire equipment should be protected so that there should be no danger from commutator sparks, from fuse flashes, from flashes from starting rheostat contacts, or from open circuits or broken wires.

Means of Protection. A volume could be written on the various experiments that have been made in connection with explosion-proof motor protection, but it is sufficient to say here that one of the most effective means that has been devised for the purpose is to provide the frame of the motor with relief openings of comparatively large area, by placing side by side about one half millimeter apart, plates of metal about one half millimeter thick. The flames of an explosion that may occur inside of a motor casing, as they pass out between these plates, are cooled below their ignition temperature before they can escape from the motor casing and ignite any gas that may surround it. This form of protection has been found to be extremely effective and is of a type that lends itself to rugged mechanical construction.

Having by this means secured an explosion-proof casing, the next step is to install in this casing the contacts of the starting rheostat and the fuse or circuit breaker that is used with the motor. It is also desirable to run all wiring inside of the explosion-proof casing as far as possible, and when this can not be done the wires should at least be covered by the metal parts of the machine frame so that it will not be possible to break them. Since the wires can not be protected all the way from the source of power to the motor, there must be some point where the wires must shift for themselves, so to speak, and in the case of coal cutting machines this point is comparatively near the motor; *i.e.*, in the trailing cable. The trailing cable of coal cutting machines receives very hard usage but it should be inspected daily, and by so doing the chance of its becoming a source of danger as far as gas is concerned is very slight. However, it is advisable to reinforce the cable where it enters the rigid frame of the machine so as to prevent the breakage that is so likely to occur at that point.

Experimental Work. As previously suggested, a great deal of experimental work has been done in connection with the subject of explosion-proof motors. As far as I am aware, the first important work was done by Bergassessor Beyling in Germany. Some time ago the Bureau did a considerable amount of work in this connection, the results of which are reported in Bulletin No. 46, copies of which may be obtained by addressing the Director, Bureau of Mines, Washington, D. C. As a result of these preliminary experiments the Bureau established a schedule of fees for testing motors, so that the Bureau can now make tests for manufacturers to determine whether or not their machines can be approved by the Bureau as explosion-proof. Technical Paper 101 will be issued in a short time describing the results of the first tests of this sort that have been made. Copies of this Technical Paper can also be obtained by addressing the Director, Bureau of Mines, Washington, D. C. The following abstract from this paper may be of interest at this time as describing the principal features that the Bureau considers essential to the design of explosion-proof motors.

ABSTRACT FROM BUREAU OF MINES TECHNICAL PAPER 101

Design and Construction. The design and construction of permissible explosion-proof motors and their accessories must be especially rugged. This requirement will be applied consistently to all the details of the machine as well as to its principal parts, in order to be assured that, under the severe conditions imposed by mining service, the explosion-proof qualities of the equipment will remain unimpaired.

The protective devices used with permissible explosion-proof motors must not only be capable of preventing the passage of flames from the interior to the exterior of the motor casing but such devices must also possess sufficient mechanical strength to insure against the accidental destruction of their protective qualities. If there are moving parts in connection with such devices, they should be so designed that there can be no interference with the movement of such parts.

Starting Rheostats. Starting rheostats and other necessary equipment that may cause an ignition of gas must be protected as adequately as the motor itself. The casings of starting rheostats should be explosion-proof. The resistances and contacts of the starting rheostats used with portable motors of not more than 50-h.p. capacity should be enclosed in the same box, unless enclosed in separate boxes connected by approved piping through which all leads are carried. All leads entering the explosion-proof casings of starting rheostats should pass through the casing in the form of properly protected, insulated studs of approved design. The use of rubber bushings will not be approved because the bushing may become displaced and thus destroy the explosion-proof quality of the casing. The casing of the starting rheostat should be mounted on the motor casing, if possible, and the inter-communicating openings for the passage of leads should be made large in order to prevent the rise of pressure that always attends the propagation of an explosion through a small hole from one compartment to another.

If it is not possible to mount the starting rheostat on the motor frame, all leads connecting the starter with the motor should be carried in rigid metallic conduit.

Unless means for opening the circuit both automatically and by hand are provided in a separate explosion-proof casing, they should be incorporated in the design of the starting rheostat. If the starting rheostat is mounted on the frame of the motor, provision should be made for entirely disconnecting the electric circuit from the starting rheostat.

Motor Casing. All joints in the casing of a motor or of any of its accessories must be metal to metal joints with faces not less than one inch wide, and if the pressure developed in the motor casing by explosions can exceed 50 lb. per sq. in., the faces must be not less than 1½ inches wide. All bolt holes in casings must be bottomed, or so arranged that the accidental omission of a bolt will not give an opening through the casing. All openings in the motor casing other than those provided with protective devices by the manufacturers must be tightly closed. It is desirable that such openings be as few as possible. There should be no exposed terminals or contacts outside the motor casing. If there are glass covered openings in the casing of a motor, the glass should be of ample thickness and should be protected by strong metal covers that close automatically unless held open by hand. Armature bearings must be so designed that under no circumstances can an explosion be propagated from the interior of the motor casing around the armature shaft or through the oil wells.

Cable Reel and Trailing Cable. If there are any sliding or rubbing contacts in connection with the cable reel, such contacts should be provided with explosion-proof protection, and any plug connections should be constructed so that they will be explosion-proof. At the point where trailing cables enter the frames of portable motors, the cable should be protected with suitable armor or flexible metallic conduit, securely fastened to the frame of the motor, and of a sufficient flexibility to prevent short bends from occurring in the cable. The cable should not be fastened to this armor, but there should be provided inside the frame of the motor, an insulated clamp of approved design for securely fastening the cable and taking all mechanical strains that may be put upon it.

THE LIMITATIONS AS TO CAPACITY AND TYPE OF MOTOR WHICH MAY BE THROWN ON OR USED ON SYSTEMS, FROM THE STANDPOINT OF CENTRAL STATION COMPANIES

F. A. Allner: From the standpoint of central station companies the size and type of motor connected at any point of the system has seldom any other limitation than the one as affecting the voltage regulation. The starting current of a motor, no matter what the type, will furnish, as a rule, the most severe condition for the motor installation, as far as affecting the voltage regulation either on this particular distribution feeder or on the entire system. There are few exceptions where special duty conditions may cause heavier currents than starting or normal running, in the nature of over-loads of short duration, such as motors driving stone crushers, grinding mills, presses, etc. In such cases, of course, the most severe drop in regulation has to be investigated.

By far the majority of central station companies in medium size and large cities, maintain an a-c. and d-c. distribution system. The latter can be traced back generally to some pioneer Edison installations and is often restricted to the down-town districts, serving lighting and only small motor customers. The 60-cycle a-c. system supplies the balance of the distribution service, except in those cities where the prime movers generate at 25 cycles and feed a number of large individual power consumers, traction systems, and special industrial districts directly with the 25-cycle service.

In every instance of a larger motor installation the effect of the most unfavorable starting condition on the supply circuit must be examined. As an extreme limit a voltage drop of 10 per cent for such feeders as are not connected to any lighting load, and of 2 per cent for mixed power and light feeders, is permissible. Such heavy drop would be met with very rarely because the present practise of using distribution voltages of 2200, 6600, and even 13,200 volts for larger industrial power service, combined with the minimum standard cross-section of 6 B. & S. standard gauge can easily take care of the drop caused by the starting current of an individual motor. The conductor material for the over-head or underground distribution system, as a rule, is standardized to the use of about half a dozen cross sections and once the voltage and transmission system is decided upon, the choice of the conductor is generally only a limited one.

In the case of mixed power and light load, very often the installation of a separate step-down transformer for the lighting supply will solve the question of voltage drop on a given feeder, because the major part of the reactance lies in the distribution transformer between feeder and motor.

The extreme limit of 10 per cent for the voltage drop in power feeders may have to be reduced considerably wherever special service conditions would call for a closer voltage regulation of motor load, necessitated, for instance, by rigid constant speed requirements of induction motor drives in textile or paper mills.

For smaller motor installations the rules guiding the consumer and the central station company, as issued or approved by the Public Service Commissions, generally bring the voltage drop in actual practise considerably below the permissible limit of 2 per cent on mixed lighting and power feeders.

In the case of the Baltimore Consolidated Gas, Electric Light & Power Co., for instance, all motors over ½ h.p. must be either for 240-volts d-c.or 230-volts a-c., which is twice the regular lighting voltage. To simplify distribution in service districts composed of small individual loads, all a-c. motors up to 10 h.p. must be single-phase motors, excepting only elevator motors and such installations where a contract has been made for installing within one year more than 10 h.p. motor load. In regard to single-phase motor installations, all sizes above 1 h.p. must be of the commutator type, excepting only installations for stationary vacuum cleaners. The type of motor developed for this latter drive has proven to require relatively small current when starting, favored also by its starting without mechanical load.

For single-phase motors over 2 h.p. a limit of 1½ times full current must not be exceeded, to be secured with starting resistance or another equivalent device.

Three-phase motors of 5-h.p. capacity and over, must be of the wound rotor type, excepting only especially large installations in which case the percentage capacity of the largest squirrel cage motor on a 60-cycle feeder must not exceed 15 per cent of the total connected load of the same voltage and phase system; and on 25-cycle lines, 25 per cent. The limit for the starting current of larger phase wound motors is set at 1½ times the full load current.

The squirrel cage motors of 5 h.p. and over that are exempted from the phase-wound rotor rule, have as limit for their starting current three times the full rated load current.

In the case of elevator motors, single-phase installations up to 20-h.p. rating are permissible. This exemption is made to allow on outlying districts with only single-phase feeder lines, the connection of elevator loads in buildings, where neither the consumer nor the central station would be justified in incurring the investment of the third wire addition.

In case of three-phase elevator motors of 5 h.p. and over, reverse current relays are prescribed. The latter rule is for the purpose of avoiding the accidental reversal of rotation in case a lineman should have made a mistake in re-connecting his phases.

For all direct-current motors the limit of the starting current is set at 1½ times the full rated load current, a condition which in no way works a hardship in the design of the motors and their starting devices.

It is frequently to the interest of the consumer as well as central station company to arrange the total motor load of a customer in a number of individual drives each of which will not exceed in size the permissible limit of the squirrel cage type motor.

For larger individual motor installations special conditions might arise in the nature of limits to starting current that must be considered from the very beginning, in the cost of installation to the central station company, in the design of the motor, etc. Not only the maximum starting current, but equally the power factor under which it is drawn, will determine the voltage drop of the feeder. A phase-wound motor compared with a squirrel cage motor that draws the same maximum starting current will cause a considerably lower voltage drop and therefore, the phase-wound type of induction motors will be more frequently used for the larger sizes in districts where the feeder lines are not of excessive capacity.

From the central station company's point of view the synchronous motor type is to be preferred over the induction type, on account of its better power factor operation, unless the power factor on the feeder does not drop below a reasonable limit, approximately 70 per cent; or when the large per cent of synchronous load on the rest of the system compensates for a poorer power factor on some particular feeder line. On the other hand the more complicated method of starting, the higher first cost, and the injection of the additional exciter system, may often warrant the synchronous motor type, despite the better efficiency, only in such cases where expert attendance is available, due also to other conditions at the consumers premises. Above a certain size the auto starter is not as desirable a starting device as other starting methods although it is the most desirable arrangement for the consumer, approaching conditions of the induction motor.

The generating capacities of central stations in medium size and larger cities are generally such that a voltage drop at the station buses caused by the throwing in of an especially large motor on the system, very seldom exceeds the permissible limits. Such voltage drop, of course, being instantaneous in character cannot be taken care of by any automatic regulator; the regulation characteristics for different power factors taken for the smallest generating unit that may be connected alone to the bus when this particular motor may be started, must be investigated and again, as extreme limit, 2 per cent drop should not be exceeded.

From the operating point of view the induction motor shows superior stability in staying in step over the ordinary type of synchronous motor, at such times when voltage and frequency fluctuations, short circuits, etc. befall the system, originating at the central station or on some of the transmission or distribution feeders. This condition, however, can be taken care of to a certain extent, also, on the synchronous motor, by equipping the field with adequate damper windings, thus making the synchronous motor act, at times of voltage and frequency variation, similarly to an induction motor.

There is a certain relation between the resistance of the damper winding, the starting current, starting torque, and the synchronizing torque. A higher resistance of the damper windings gives higher starting torque for a given current, but results in lower synchronizing torque. Such synchronous motors with high damper resistance could be started with no mechanical load by means of an auto-starter under low starting current and good power factor conditions.

On the other hand, a motor with very low damper resistance would give heavy starting current, but low starting torque and may not start at all even with full voltage applied to the stator leads. The synchronizing torque again, *i.e.*, the force required to pull the motor out of step once it had been locked into synchronism, is considerably larger for this type of motor.

Depending on the special service conditions and the maximum mechanical load under which such a synchronous motor should pull in step again at times of voltage and frequency disturbances, the design of the damper winding has to be carefully selected so as to secure all desired advantages without incurring any draw-backs. Properly dimensioned damper windings do not necessarily decrease the efficiency of the motor, even with their pitch smaller than the spacing of the stator slots, although the theory seems to point in the other direction.

Larger sized synchronous motors, directly connected to mechanical loads, may render a valuable assistance under certain conditions for the improvement of the power factor of a feeder district or of the whole system, in the same manner as any other synchronous apparatus, such as frequency changers, rotary converters, etc. Under special conditions very extensive use can be made of this power factor correction, when this feature is taken care of from the very beginning in the design of the motor.

Although only over-excitation is generally desired by any method of abnormal power factor operation with synchronous apparatus, conditions may also turn up on a distribution service that is tied in to a high-tension over-head transmission system whereby a very low limit of under-excitation is desired for the purpose of creating sufficient reactive current, during off peak hours, on the over-head line to prevent sleet formation.

Central stations supplying power to interurban or longer suburban traction systems, operating on single phase, are sometimes confronted with the decision whether to tap the single-phase supply directly from the three-phase system, or split the track in sections, supplied by different phase current, or to produce the single-phase current by the use of phase changers. In one particular single-phase traction installation about eight years ago, when the central station had a capacity of only four 2000-kw. generators with a possibility that only one generator might be on the bus when a heavy traction pull might occur, three 600-kw. synchronous phase changers were installed, generating single-phase current at 6600 volts for feeding the near section directly at that voltage and the more remote section through 22,000-volt single-phase step-up transformers. This three-phase energy was taken by the synchronous motors at about unity power factor from the 13,200-volt generator station buses.

From the very beginning, provision was made for the ultimate elimination of the phase changers and for adopting the single-phase step-up transformers in Scott connection for feeding the traction system with two-phase current, the windings being arranged so, that one phase fed with 6600 volts the nearest section, while the other phase supplied 22,000 volts to the sections further away.

This change over was actually carried out a few years later after the generating capacity of the station was more than doubled and no difficulties, due to the unbalanced phase current, combined with lower power factor, were experienced. The power factor, however, under which the new system operated was so much lower compared with the original phase-changer installation that the kilovolt ampere hours measured at the station buses of the new system equalled, approximately, the previous kilowatt-hour supply. In the original layout the overall daily efficiency of the phase-changer sets was around 65 per cent, this figure equalling approximately the average daily power factor under the changed method of operation. About one year after this change the entire system was finally re-designed for 1200-volt d-c. service, resulting in a very considerable saving of power consumption.

THE FACTORS INVOLVED IN MOTOR APPLICATIONS

Harold Goodwin, Jr.: I wish to draw your attention particularly to the viewpoint of the central station; first, in regard to the choice between direct current and alternating current, and following that, the particular factors we must consider when we have made the choice.

The first question to arise is: Is the central station related to all motor applications, or if only to a portion, to what portion? Some of us say it is related to them all, while statistics say it is related to only part. The real question is: What will be the ultimate relation? If we again answer that the central station will ultimately be related to every motor application, we cannot prove it. But we *can* point to the very great increase of central station service for motor purposes during the past few years, exceeding the brightest hopes of the early days, and we *can* point to the parallel of the great increase in voltage of high-tension transmission above anything that was predicted. That the discussions at the Industrial Power Committee meetings show either general assent or dissent to the proposition of universal central station service is most important, not only for the engineers of the future who will have to deal with the problems we create for them, but also for ourselves, that we may be able so to design the central station and all current consuming apparatus, that the day when they both will be linked together may come the sooner. That in some cases at the present time there seems to be no chance for economy by the use of central station service I perfectly agree, but that future developments with increasing density of load will change a large number of these cases I am perfectly positive. Even now there are very few plants which would not benefit from being able to throw their whole load to central station service in case of a breakdown of their own apparatus.

The idea of central station service is so generally accepted at the present time that it may seem out of place to devote time to it here. But while it is generally accepted, each individual who does not use it thinks that his is the special exception and stops to consider it a few years before he will accept it. If there are then processes which inherently have no relation to central station service, the records of meetings of the Industrial Power Committee should show them.

Having decided that all installations should be related to central station service, the next question is: What is the form of central station service to which they should be related? The answer, like all true engineering answers, is of course expressed in dollars and cents; that is, the characteristics of the central station service should be such that the cost of the power delivered from all motors to the apparatus will be a minimum. This total cost is made up of two items—the cost of the power supplied by the central station, and the cost of the installation. Let us look into these two items, and see to what extent they have both been developed, and where the future possibilities for development lie. If we find that one has been developed to its limit while its alternative has not, we may find there is an easy solution of the problem without a consideration of the complexity of all the detail factors involved.

Taking first the question: What is best in central station service? The answer is, the most efficient. What then are the systems which we are to compare in order to find the most efficient? The main divisions with which we are all familiar are direct current and alternating current. In order properly to compare these systems, we must first pick out the most efficient arrangement of each system. Almost all d-c. distribution is underground, so to find the standard d-c. construction we naturally turn to the report of the Underground Committee of the N. E. L. A. The best answer we find here is in the recommendation of last year's Committee to this year's Committee that consideration be given the following:

"Comparative practise in d-c. distribution, giving standards used by different companies for different items, such as size of mains and neutrals, type of junction boxes, use of single conductors versus concentric cables and limiting size of same, practise as to fuses, etc."

This does not appear to give us a very good standard from which to construct our ideal d-c. system for comparison with the alternating-current system.

Turning to alternating current, we find that much has been written on construction methods, but when we search through all of this we seem to get scarcely closer to the standard solution of our problem than is the recommendation quoted above on d-c. distribution. This much is found, that direct current has had its application in the dense load sections. Underground alternating current has also been supplied under these conditions, and a careful analysis, though never published, has shown a balance in favor of the alternating current, at least as far as lighting is concerned.

If we therefore cannot find some general solution to the problem, by the comparison of the best in direct current with the best in alternating current, let us see if we can find a solution in some particular case, and then see how far this can be extended to cover the whole. There is one class of service which is acknowledged by all to be more economically supplied by alternating current than by direct current. This is service to residential and suburban sections of cities, farming country, and, in fact, all scattered and light loads. This means that a large portion of the territory now supplied by electricity is supplied by alternating current, and that practically all new territory will be supplied by the same. But if in dense load sections the alternating current and direct current are of nearly equal economy, and concede even that it may be proved that direct current has a slightly better economy under certain conditions, the question arises, will it ever be proper to change from alternating current to direct-current distribution with increase of load? This fortunately is not difficult to answer. By the time the load has increased to an extent such as to allow serious consideration of direct current, it will have increased, due to a large amount of apparatus built especially for alternating current, the cost of changing which from alternating current to direct current will be prohibitive. So even assuming that the cost of distribution by alternating current and direct current in dense load centers is easily comparable and not in favor of alternating current, we find that alternating current is the ultimate answer, provided, however, that it will be suited to the service which is required of it, particularly in its application to motors.

As we have found a definite limit in d-c. distribution, let us now investigate and see if there is a definite limit in either d-c. or a-c. motor practise. We find first that a-c. motors have various advantages over direct-current motors in regard to constancy of speed, elimination of commutator troubles, etc., but that in variable speed work the d-c. motor has a distinct advantage. While we believe this has been overcome, there are many who still believe that the d-c. motor has a great advantage over the a-c. motor for crane, elevator service, etc. Is this lack of variable speed characteristics then the limit for a-c. motors as the distribution in residential sections is for d-c.? In the distribution question there is no item of cost which if it could be reduced would not effect equal reductions in both forms of distribution. Now, will any improvement which may be made in the a-c. motor have an equally beneficial effect on the d-c. motor? The answer is without discussion, "No." The d-c. motor has been developed to practically its limit, while the a-c. motor, though it is highly developed in many ways, has still room for great improvement, particularly in variable speed service. But is this improvement possible? The answer from an engineering point of view is "Yes," though from a commercial point of view that word cannot yet be spoken very loudly.

The objection to lack of speed control is on the part of the customer. What are the objections to the a-c. motor from the central station point of view? Its heavy starting current and poor power factor are the chief characteristics looked on with disfavor. Is it possible to overcome these? Both have been largely overcome, though there is still much to be desired in the ordinary commercial motor.

What then is our answer to the question—direct current or alternating current? Emphatically—alternating current. The direct current has present and ultimate limitations, while the alternating current has only a few present limitations along certain lines, and these are being rapidly overcome. But, it may be argued, since the high-tension transmission and a-c. system generally have been developed so much more highly than was anticipated a few years ago, may not the wireless transmission of energy or some other such new development supersede the alternating current? It may and we hope for all possible improvements. Should this come, it may replace the present transmission, or it may affect the wiring for lighting in a house, but a motor will always be needed to give mechanical power and some delivery and metering devices will be necessary for supplying lighting or power. So it is not likely that a distribution system with an efficiency such as is possible with the present a-c. system will go out of date for many years to come, and when it does pass it is probable that most of it will be readily converted to the use of its successor.

Before considering the subject in detail, let us look at the proposition in general. What have the central station companies told the manufacturers that they want in regard to motors? Aside from what the operating engineers have told the manufacturing companies they desired in certain particular cases, the only information which the manufacturing companies have on the requirements of the central station are those published in the general rules and regulations of the central stations. Mr. J.

C. Lincoln's paper on "Line Disturbances Caused by Special Squirrel-Cage and Wound-Rotor Motors" criticised the general rules and regulations of operating companies. The only objection I have to make to his criticism is that it is too mild. The general rules of operating companies up to the present time are a collection of a great mass of inconsistencies and impossibilities, with a few truths scattered through them. The general mistake has been made throughout of defining a means to an end without also defining the end. The same means may with a slightly different application give some other than the desired end. I refer particularly to the requirement in some companies that single-phase motors start as repulsion motors, without also stating the maximum starting current, assuming simply that any motor started in this manner will be far superior to any split-phase motor. Provision is also made for auto starters and wound-rotor motors without also providing what the limit of current shall be when these starters are used. In connection with elevators it is very often stated that the motor shall be of the wound-rotor type, yet there is nothing in the rules to prohibit the use of a simple dash pot for controlling the wound-rotor resistance. The resultant operation may have absolutely no relation to the line current, the thing objectionable to the central station, and for the control of which these devices are required.

The first step, therefore, that the central stations can take toward the improvement of the objectionable characteristics of a-c. motors is to agree on rational possible rules showing the requirements which they desire, and indicating also the particular lines along which they desire to have the manufacturers make developments. Fortunately, the Electrical Apparatus Committee of the N. E. L. A. has taken up this matter, and their report to the convention in June will doubtless be of great value.

Considering now the fractional h.p. motors, the chief objection of the central station to these is their heavy starting current, which is usually applied directly to the lighting system. The poor power factor is of not so great moment. A large number of the ½-h.p. 110-volt motors now on the market take a current in starting from 30 to 50 amperes or even more. This is equivalent to the whole load of from 6 to 10 of the small stores in which such motors are usually used, and it is obvious that a distribution system cannot be economically designed to care for the ordinary lighting demand and yet be prepared to carry such heavy, sudden currents. Also the great recommendation for these motors is that they can be easily attached to the present wiring or lighting system, or they form the opening wedges for a lighting installation.

I agree with Mr. Lester's first statement that very little space has been devoted to the fractional h.p. motor in technical literature, and it is very easy to see from what I have already said that I agree with his second statement, that the subject presents certain difficulties. I further agree with his three reasons for the great development of the small motor field. However, when he comes to list the general points to be considered, he gives as one: "Variation in the characteristics of the circuit on which the motors are to operate, such as variations in voltage, frequency or both." But he does not give the consideration to the variation in voltage which the motor will cause on that circuit. His reference to "light wiring or insufficient transformer capacity" as a cause for poor starting torque, is adding insult to injury. He puts the small split-phase motor forward as a class on account of its portability and easy miscellaneous attachment, and then objects when the voltage at a socket supposed to carry 40 watts drops due to a demand which in some instances has been carefully measured as 1.6 kv-a. for a $\frac{1}{8}$-h.p. motor. He acknowledges that the chief good which a centrifugal clutch on a split-phase motor can do is to reduce the time during which the starting current is drawn, but he does not claim that it materially reduces the starting current, which will therefore still give a serious flicker to the lights connected to the same circuit.

The suggestion that rulings should specify in amperes the permissible current which motors may take, corresponding to established voltages, is excellent, and it is further suggested that this may be measured by ability to start either once or a specified number of times per minute on a given fuse. This is the easiest and most practical method of demonstrating to customers and wiremen the current which the motor draws. This may appear to be a disproportionate amount of space to devote to fractional h.p. motors, but at the present time they constitute one of the very greatest problems of the distribution engineer.

The problems connected with the larger motors, as has been stated before, are those of starting current and power factor. The question of starting current should be possible of solution by a frank, intimate and detailed discussion of the facts, and it should be possible to arrive at a conclusion satisfactory to most of the manufacturers and the central stations. To this discussion Mr. J. C. Lincoln's paper on the special squirrel-cage motors is a very great contribution, and a reply from the advocates of the wound rotor should enable the central station to write rules which it would be possible to meet, and which would require the best in design of either type of motor.

The question of power factor is a very important one. It is quite customary to state that induction motors have a power factor of 80 per cent to 90 per cent, yet this is under full load conditions. Under the conditions under which many of them operate for hours in actual service, the power factor is nothing like this. Some feeders to which are connected only high grade motors have been observed to run as low as 30 per cent power factor showing load variations on the power factor indicator rather than on the ammeter. One remedy for this trouble for the central station is of course to base the charges on the maximum demand in amperes, but this is open to much discussion, and the fact that the central station may be compensated for the loss does not do away with the fact that there is a great loss.

That it is possible to overcome this loss has been shown by the design of at least one unity power factor induction motor. This is an expensive motor, but it shows the possibilities, and the manufacturers should lend their aid in developing motors with unity power factor characteristics along commercial lines.

It is now interesting to try to discover what the distribution engineer is trying to do to overcome these acknowledged difficulties. To overcome the customer's objection to a-c. motors, that is, to the low starting torque and non-variable speed characteristics, the installation of either mechanical devices or motor-generator sets or rotary converters to supply direct current is being recommended. Under the present conditions there still seem to be places where no other recommendation than this can be made.

To meet the distribution problems, what is being done? What progress is being made in overcoming the effect of motor starting currents and poor power factor on the lines? To overcome the present troubles the erection of transformers and running of additional secondaries, is the usual remedy in aerial districts. But one man has gone ahead of this. Mr. Schweitzer of Chicago has designed and built, very cheaply, an automatic instantaneous voltage regulator. This is in principle a current transformer. Connected to the service and supplying lighting through one leg and power through the other. The windings are so connected that the lighting voltage is raised an amount just equal to the line and transformer regulation when a motor is started and operated. It still leaves some things to be desired, but it is progress toward a transformer without regulation, and even in its present form should have a great field. Unfortunately the motor problem in underground districts is not being handled even as well as in aerial districts. Instead of erecting transformers and secondaries, d-c. mains of various voltages are being extended in many places. This is not only side-stepping the problem, but it is imposing a greater burden on those that will follow and on engineers in other cities who are trying to meet it.

In this discussion I have not touched particularly on large power installations because it is recognized that to transmit large blocks of power to a customer the use of alternating current is necessary. It is therefore to the advantage of both the customer and central station to make the installation alternating current throughout. On new work this is quite generally being done, except in cases which present the problems of speed control already discussed, in which cases it is necessary to install motor-generators or rotary converters. The supply of current through synchronous apparatus for railway operation, electrolytic processes, large motors, and existing large plants operating from direct current, will give enough synchronous apparatus on the lines so that there is little force to the argument for installing rotary converters and d-c. motors in preference to a-c. motors to get the power factor correction which can be obtained with synchronous apparatus.

Summing up what I have tried to bring out:

(1) All motor applications will ultimately be related to the central station.

(2) Alternating current is the ultimate in distribution, and all developments should be made with this in view.

(3) There are objections to a-c. motors, but these may be overcome by a careful statement by central stations of what is desired, followed by a careful study and development by the manufacturers along these lines.

There is no greater need at the present time than a good summary of the present knowledge in a-c. distribution, including the method of overcoming all of the problems which are met, particularly those connected with motor applications. If the discussions connected with the meetings under the auspices of the Industrial Power Committee can bring out all of these points, there could scarcely be a greater benefit bestowed on the engineering industry.

LINK-BELT SILENT CHAIN

C. R. Weiss. In 1901 began the sale of what was termed the "Renold Silent Chain Drive"; the patent rights to manufacture the chain in the United States having been obtained from Hans Renold, Manchester, England. The chain in question, I might state, was of the same general form as our present silent chain and those of other well known manufacture. At that time the joint consisted of a plain circular case hardened pin joint, *i.e.*, consisting of a round unprotected hole in the link and a cylindrical pin in direct contact with holes in the separate leaves. More or less trouble was experienced with this construction, due to the elongation into elliptical shape of the holes in the links, and to the rapid grooving of the pins, from the unequal distribution of load across the pin area. The aggregate caused very uneven action and rapid wear of the wheel teeth. Neither copious lubrication or case-hardening of the links overcame these defects.

With construction as mentioned it was apparent that the chain was unstable and that it could not be placed before the public on account of short life.

In 1904 Mr. J. M. Dodge evolved and patented the split bushed joint. This consisted of segmental liners or bushings, which are removable, extending across the entire width of the chain, thus doubling the bearing surface and halving the unit bearing pressure on the joint. The bushings are case-hardened and bear upon case-hardened pins, which are free and rotate with reference to the bushings, thus presenting every particle of surface for wear. As a result the joint wears uniformly, keeps round and maintains to the end the high initial efficiency.

The drive is applicable to every case where motion is to be transmitted from one shaft to another. As the sustained efficiency is approximately 98 per cent, it is evident that the saving of power, as compared with belts and spur gears with an efficiency some 5 to 10 per cent lower, is a very important item; but this is not all. First, bear in mind that the silent chain fits approximately one half of the total number of teeth in both driver and driven wheel simultaneously. Consequently there is no slipping as with belts, nor jumps and vibrations as with worm gears. In fact the drive is as positive as a gear drive and as flexible as a leather belt drive with the added advantages as opposed to gears, of non-fixed center's and as opposed to belt drives, of greater possible compactness and low initial required tension.

Take the case of machine tool drives. The driving force through a chain, positive but elastic, is equal at each instant to the force required to do the work at the rate of feed and speed to which the tool is set, meeting unflinchingly the requirements as they arise. A steady uniform rate of work is the result. The deflections in the machine parts are held constant, and the tools cut away the metal as opposed to the tearing and chattering that occur with the shock of high speed gears, or with the creep and slip of leather belt drives.

The results have been found to be: greater output, saving in power, less wear and tear on cutting tools, better efficiency, and that heavier cuts can be taken on the same machine.

On punch presses, shears, etc., the drive has produced vastly superior results on a service to which at first it was believed a positive drive was hardly applicable, but as a matter of fact the chain drive is less severe on a motor armature than a belt drive. With the former the flywheel is always up to speed at the instant of punching and this energy can be relied upon to assist the motor. The chain is flexible enough to relieve the motor armature of sharp shock. The overload, due to slowing down, is of too short a duration to generate objectionable heat. On the other hand with the belt drive the belt will often slip just as the punching is completed and the flywheel will not pick up speed during the next stroke. The result is an overload on the motor. Thus again the advantages are, greater output, economy of power consumption, less wear and tear on cutting edges, and more uniform product.

The silent chain drive has proved particularly adaptable to fans, allowing for short centers and economy of space, one particular case in mind being a 240-h.p. mine fan drive, which operated continuously day and night for over five years, the only direct charge against this drive being oil for lubrication. It was never necessary to shut down for one moment of repairs to the chain.

Blowers and compressors lend themselves to silent chain drive for the same reasons as do fans. However, it is necessary that the machine be of good design, in that sufficient flywheel effect is provided. This of course also applies to machines for refrigerating purposes.

A large number of paper mill installations, and a majority of chain-driven paper mills, use link-belt silent chain.

Numerous drives have been sold for operating generators and exciters from steam engines, allowing of compactness and avoiding all detrimental effects of atmospheric conditions to which a leather belt is subjected.

The rubber mills also present a field well adapted to silent chain drives, especially as opposed to direct gearing, in connection with which it is necessary to have self contained bases and the most rigid of construction.

I might go on indefinitely and tell you, for instance, that in the South particularly there is an enormous field for the silent chain drive in textile mills. I have one case in mind, the Interwoven Mills of Martinsburg, W. Va. This mill is now completely equipped with silent chain drives, 105 in number, most of them being over four years old. In this plant, due to the positiveness of the drives, seconds or goods showing defects, have been eliminated. Note this: that the positive drive has also been responsible for the elimination of broken ends, which cause shut-downs of the machine. Consequently an operator can attend to one-third more machines, greatly increasing his or her earnings and greatly increasing the value of the firm's product. At this date it is felt that the drives have not only paid for themselves, but are real dividend makers.

Another interesting installation is that in the shops of the Reading Iron Company of Reading, Pa., which consists of 50 30-h.p. drives, operating socket tapping and threading machines. The majority of these drives have been in operation over five years under conditions so severe that the former method of driving, which consisted of belts and gears, would not stand up and proved a very costly and troublesome method practically eliminating any prearranged quantity of production. As I previously stated, these drives are not running under what would be termed favorable conditions, but the lubrication is looked after carefully. The flexibility of the drive has overcome the greatest objection, gears; and has absorbed the unequal motion that was transmitted to the motors by the gears. To use the plant superintendent's words, " I would say that silent chain is far superior to the belt or gears and in addition is so sweet on the motors that motor difficulties have been eliminated."

The motor car has presented a varied field for the silent chain drive, in the operation of timing gears, magnetos, generators, starters, etc.; and at the present time a large volume of work is being fabricated for various makes of cars.

And now a word as to the drive. The chain details have been previously explained. The wheels on which the chains operate have cut teeth of special design, there being no rolling, sliding action between the working faces of the links and the faces of the teeth. As the link-belt chain is symmetrical, it can be operated in either direction.. When wear is disclosed on the wheel teeth, these parts can be reversed, presenting unworn surfaces. Further, the chain is of such construction that it can be easily and quickly repaired by renewing the joints if worn, thus bringing the chain back to more nearly its original pitch.

The drives have to be designed to meet certain requirements and for all ordinary conditions engineering data is given in our hand book No. 125, which enables any engineer or mechanic to select a proper drive. In selecting any drive it is desirable to select pinions containing an odd number of teeth, in order to gain what is known as a hunting tooth effect. This is due to the manner in which chains are built, the links in adjacent pitches being staggered to permit of assembly. Therefore with a 17 tooth pinion we gain the effect of 17 working teeth, as far as wearing value is concerned, while with an even number of teeth only half the number of teeth are effective.

Selection of the proper size chain depends on the old formula: Work = force in pounds × distance in ft. per min.; and h.p. = work divided by 33,000 ft. lb. per min. Interpreting the formula as we desire it: Force in pounds or chain pull = h.p. divided by chain speed. This arrived at, it is essential that the proper safety factor be selected. After many years of experience it was learned that such safety factors must be used as would give wearing and bearing value consistent with long life. To this end have been computed tables and formulae from data collection, which have proven that considerably lower values can be used at low chain speeds than at high speeds. It has also been determined that for unit increases in speed, the power transmittable rises per foot per minute from speeds of about 200 ft. per min. on up to speeds of about 1500 ft. per min. in proportional amounts. Above this speed the power increases decrease manifestly on account of the high inertia strains which are inherent with the high speeds.

For high speeds and low powers fine pitch chains, such as ⅜ in. and ½ in. are employed, whereas for heavier work the chain pitches increase proportionately.

At the present time chains are made of pitch and width to meet certain conditions of the proportion of pitch in inches and width in inches in the ratio of 1 to 16, or in other words, a ¾-in. chain 12 in. wide, or a 1-in. chain 16 in. wide.

Where speed conditions are such that would of necessity employ a 1 in. pitch 32 in. wide chain, two strands of chain are used with an equalizing device in the driven wheels similar to the single tree of a double team wagon, which device will insure that each chain will assume its share of the burden. It is practical to equalize any number of strands by a specially devised arrangement. In some cases multiple strand drives have been operated non-equalized, but the element of chance is there, especially as one chain, due to various elements, is apt to receive more wear than another. The difficulties arise in endeavoring to make the chains pull together and it is almost impossible to compensate for this unequal wear by the substitution of new parts.

Certain characters of work, such as brick manufacturing plants, cement mills, etc., expose the drives to so much grit that it is necessary to employ dust- and oil-tight casings to afford the necessary protection; whereas in the ordinary, or commonplace shops, the drives can be run open. Most States, however, require that all machinery be protected and many of our customers encase the drives and operate them through oil on account of the factory requirements.

THE SELECTION OF MOTORS FROM THE POINT OF VIEW OF FREQUENCY, VOLTAGE AND PHASE, AND THE INFLUENCE OF VARIATION AND UNBALANCING OF SAME

CHOICE OF FREQUENCY

A. M. Dudley: There are, in more or less general use on our continent, the following frequencies, viz: 25-30-40-50-60-66⅔-125 and 133 cycles and possibly some others where local conditions seem to demand it. Of these the two entitled to the most serious consideration are 25 and 60 cycles. There are a large number of 40-cycle units in operation, but it seems to be the general policy of all manufacturers not to extend this service, and it will probably be eventually susperseded by 60 cycles.

In the discussion of the relative merits of 25 and 60 cycles I will quote very freely from a paper presented at the Eighth Annual Convention of the Association of Iron and Steel Electrical Engineers at Cleveland, Ohio, September 14-19, 1914.*

Several years ago there was an apparent tendency of the large power companies toward 25 cycles, but that tendency is now reversed, partly due to improvements in certain types of apparatus, such as rotary converters.

The principal loads handled by general power or central station a-c. plants are: first, lighting, including arc, incandescent, etc.; second, motor power service; and third, d-c. service for various purposes, such as railway, etc.

In general, there is no particular question regarding the better frequency for lighting service, for 60 cycles for direct use in both arc and incandescent lamps undoubtedly gives better results than 25 cycles.

When it comes to motors, either synchronous or induction, 60 cycles present more advantages in general, except for very low speeds; and, even in this case with synchronous machines, the choice is in doubt. In the case of induction motors, however, there are certain fields where 25 cycles will show better results. This is in very low speed work, or very low speed in proportion to the capacity. It is a rule in practically all types of generators and motors that the greater number of poles, the greater must be the total magnetizing ampere-turns. In windings excited by direct current the number of exciting turns may be increased with increase in the number of poles, at a certain expense in copper, so that the actual exciting or magnetizing current may not be excessive, even with a very large number of poles—that is, in very low speed machines. But in induction motors the same turns are used for magnetizing and for generating counter e.m.f. The latter usually so fixes the number of turns in a given capacity and speed of machine, that the actual magnetizing current increases very greatly with increase in the number of poles, that is, with decrease in speed. With a large number of poles, this magnetizing current becomes so large in comparison with the work current that the characteristics of the machine are very seriously affected. This increase can be limited to a certain extent by increasing the dimensions of the machine, that is, its cost. Herein is where 25 cycles may give considerable advantage over 60 cycles. For instance, a 4-pole, 25-cycle motor will have about the same speed as a 10-pole, 60-cycle motor. The 4-pole motor should, and usually does have smaller magnetizing current than the 10-pole machine. However, the 4-pole machine for the same speed should require more material than the 10-pole, on account of higher magnetic flux conditions. Therefore, if the 10-pole machine were made of larger dimensions than the 4-pole, but utilizing the 4-pole magnetic material, its magnetizing current might be made fairly comparable with that of the 4-pole machine. However, with the same total useful material but arranged in larger dimensions, the idle material, such as frame, supports, etc., will be somewhat greater in the 10-pole machine of the same speed. Therefore, the cost will probably be somewhat higher. Therefore, in general, for equal speeds and equal characteristics the 60-cycle induction motor should cost more than the 25-cycle. However, for general power distribution with relatively small motor capacities, it is not correct to compare a 10-pole 60-cycle motor with a 4-pole, 25-cycle. In most cases 60-cycle motors of higher speed can be used, such as eight, six and four-pole giving respectively 900, 1200 and 1800 rev. per min., neglecting the small slip. The higher speed and smaller number of poles in general more than offset the advantages of the 25-cycle, 4-pole, 750 rev. per min. motor as regards cost and characteristics; and at the same time, the greater choice in speeds is very advantageous. In 25 cycles, the highest speed is 1500 rev. per min. with two poles. Experience has shown that, in size and construction a 2-pole induction motor has very little advantage over a 4-pole, except possibly in very small capacities. Therefore 60 cycles, with its 4-pole 1800-rev. per min., 6-pole1200- rev. per min., 8-pole 900-rev. per min. motors, has a decided commercial advantage over the 25-cycle system with its 2-pole 1500-rev. per min., and 4-pole 750-rev. per min. motors.

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*"Some Electrical Problems Practically Considered," B. G. Lamme.

However, when we compare a moderate capacity 12-pole, 250-

rev. per min., 25-cycle with, a 30-pole, 240-rev. per min., 60-cycle motor, we may find the advantage considerably in favor of the 25-cycle motor. If all the motors to be used in a given plant were of this speed or lower, and there were no other off setting advantages for 60 cycles, such as lighting, etc.; then the proposition would look good for 25 cycles. If only a small percentage of the total load is represented by such low speed motors, then the 60-cycle supply may make otherwise a sufficiently good showing to warrant its use. If we go to the extreme case of moderate or even very large capacity motors at 75 to 100 rev. per min., then we run into almost prohibitive constructions with 60 cycles, either in size or in operating characteristics. At 60 cycles, such motors are liable to have power factors so low that the actual current taken by the motors is so large compared with the work current, that even with poor performance, a very large motor is required for a given capacity. At 25 cycles the motors can make a very much better showing. Therefore, at the present time, 25 cycles represents the most suitable frequency for such motors. Hope may be extended for the 60-cycle motor. If 60-cycle motors are to be operated at constant speed or even under varying or adjustable speeds, it is possible and practicable to overcome the difficulty of the poor power factor and large current from the supply system by connecting a special low frequency exciter in the secondary circuit of the induction motor. This will supply the magnetizing current to the secondary instead of the primary, just as in the non-synchronous type of condenser already referred to. It does not eliminate the magnetizing current in the motor, but simply puts it in the secondary circuit.

The above is a considerable digression from the central station problem, but it has a direct bearing on the purchase of power by mills from central stations. From the above it is obvious that for the general sale of motor power to varied industries, the 60-cycle central station has a direct advantage over the 25 cycle in the great majority of service.

Since the general tendency of both central stations and isolated plants is toward 60 cycles and since very large low-speed units are the exception, the weight of evidence is in favor of 60 cycles for general industrial work.

CHOICE OF VOLTAGE

The general question of voltage concerns itself with the length of transmission, the area of distribution, the size of individual units, the possibility of future extensions and the voltage of neighboring power developments or stations from which emergency service might be obtained or with which future combinations may be made. In some industries the question of safety enters, owing to the nature of the work performed, and controls the final voltage.

All of these elements are largely local, with the exception of size of units. In this regard there are broad lines of standardization laid down toward which good practise is tending. Other considerations being satisfied, the following classification is representative of average conditions;

110 volts—up to and including 5 h.p.

220 volts—up to and including 75 h.p. This voltage is probably more generally used in industrial work than any other.

440 and 550 volts—7½ h.p. to 200 h.p.

2200 volts—20 h.p. to 1500 h.p.

3800 and 4000 volts—50 h.p. up.

6600 volts—200 h.p. up.

11,000 volts—not generally used on induction motors. Used on synchronous motors from 1000 h.p. up.

Where a-c. networks are to be installed in cities or in an wide spread distribution of small units at low voltage it is well to provide 110 volts for lighting and detail apparatus and 220 volts for motors.

CHOICE OF PHASE

There are in general use in industrial work three systems as regards phase; one, two and three.

Single phase is used extensively for small power motors up to 10 h.p. and comparatively seldom over that capacity. This is probably due to the fact that they may be operated from lighting circuits, which in many cases are the only available sources of power. Reliable single-phase motors may now be obtained from several manufacturers but at their best they are more expensive than polyphase motors and are not usually employed where polyphase circuits are available.

Between two phase and three phase there has been a long controversy which bids fair to result in the ultimate general adoption of three phase, if it were not for a comparatively new condition to which I shall presently refer.

In general the arguments in favor of two phase have been, that it permitted the use of two voltages in the ratio of two to one; that when the center of the two phases is interconnected either 50 per cent or 71 per cent of full voltage is available for starting squirrel cage motors and hence no auto starters or compensators are required; that in transmission and distribution only two transformers are required instead of three; that balancing lighting and other single-phase load is easier than with three phases.

The arguments in favor of three phase have been that it required only three lines instead of 4; that it is capable of connection either in star or delta giving voltages in the ratio of 1.73 to 1 without any change in transformers; that when operated in delta it permits one transformer or one motor phase to burn out and still leave the installation operative at slightly decreased capacity; that with the same amount of material in generators or motors more capacity can be obtained than with two phase by the ratio of 0.955 to 0.905 (these two figures being the respective "voltage factor" or winding "distribution factor" of the two systems); that everything else being equal, a three-phase induction motor has slightly higher torques and power factor than a two-phase motor (this difference is very slight and is more an academic than a practical point, but it has been raised in this comparison so that mention is made of it here;) that in carrying spare single-phase transformers for any part of the system, they need be only 33⅓ per cent of the total kv-a. involved instead of 50 per cent in the case of two-phase.

In weighing these several points the decision has been leaning in favor of three phase for some time, until it has seemed probable that two phase would take its place in the history of the art as having outlived its usefulness. There has arisen latterly a problem to which no final answer has yet been made, so far as the writer is aware, and upon which he would like to hear some active discussion at the present time. It is mentioned here for the reason that a two-phase system seems to be the only one that meets all the conditions, and yet for all the reasons given above a three-phase system would be preferable. I refer to the question of a low voltage a-c. network in cities. There are three conditions to be met:

1. 110 volts is necessary for detail apparatus such as fan motors, household devices, heating, etc.
2. 220 volts is necessary for general polyphase motor work.
3. One side or the neutral of all circuits must be grounded.

The first two of these are self-evident; the third arises from the necessity of grounding the neutral of distributing circuits, which is known to all central station men and also on account of the use of so called concentric wiring on single-phase circuits. This term is used to describe a two conductor, one unit wire made up of a central conductor surrounded by insulation, acting as one side for a single-phase circuit; and this insulation surrounded in turn by a hollow conductor, flexible in nature, which acts as the other side of the circuit and is at all points dead grounded. Such a conductor greatly simplifies general wiring and is considerably used in other countries.

Since this is a digression from the immediate subject it can not be elaborated here but further consideration has failed to show anything but a 220-volt, two-phase circuit grounded at the middle points of both phases which would meet all three requirements. The resulting four single-phase circuits could be handled on concentric wiring and the two-phase circuit would of course be handled as a 4-wire circuit having a grounded neutral.

There are possibly other and better solutions than this and if so the present seems to be an excellent time to air them and get an open discussion on what must in time may becom e a matter of the first importance.

EFFECT OF VARIATION OF VOLTAGE, FREQUENCY AND PHASE UPON THE PERFORMANCE OF MOTORS

The variation of these quantities can be considered as having an immediately perceptible effect upon the operation of the motors supplied from the circuit with regard to their torques and speed; and a less obvious effect with regard to efficiency, power factor, and heating. Since it is the primary function of a motor to develop torque at a predetermined speed, a certain reasonable variation is allowed in the other characteristics as long as operation is not interfered with.

On normal circuits considerable fluctuations of frequency and phase are not apt to be met with. Voltage does fluctuate to some extent and practically all manufacturers permit a variation from normal of plus or minus 10 per cent. This usually takes care of the distribution drop from power house or substation to the end of the line.

Sketching freely, the effect of variations of these quantities may be summed up as follows for machines following the ordinary rules of accepted design.

VARIATIONS IN VOLTAGE

High Voltage

(a) Increases magnetic density.
(b) Increases magnetizing current.
(c) Decreases "leakage current" (Leakage reactive component in terms of current).
(d) Increases starting torque and maximum torque.
(e) Decreases slip or change in speed from no load to full load.
(f) Decreases secondary copper loss.
(g) Increases iron loss.
(h) Usually decreases power factor.
(i) May increase or decrease efficiency and heating depending upon the proportions of primary copper loss and iron loss in the normal machine and also the degree to which the iron is saturated.

Low Voltage

(a) Decreases magnetic density.
(b) Decreases magnetizing current.
(c) Increases leakage current.
(d) Decreases starting and maximum torques.
(e) Increases slip.
(f) Increases secondary copper loss.
(g) Decreases iron loss.
(h) Usually increases power factor.
(i) Same remark as under High Voltage.

As a general rule machines of standard design will operate satisfactorily on a voltage 10 per cent higher or lower than the normal rated figure.

High Frequency

(a) Increases the speed.
(b) Decreases the magnetic density.
(c) Decreases the magnetizing current.
(d) Increases the leakage current.
(e) Decreases the starting and maximum torques.
(f) Does not change the slip in per cent for same h.p.
(g) Does not change the secondary copper loss in watts.

(h) Usually increases the power factor.
(i) Usually does not materially alter the efficiency.
(j) Usually somewhat reduces the heating.
(k) May result in overload on the motor if connected to a blower or centrifugal pump or similar load which changes rapidly with the speed.

Low Frequency
(a) Decreases the speed.
(b) Increases the magnetic density.
(c) Increases the magnetizing current.
(d) Decreases the leakage current.
(e) Increases the starting and maximum torques.
(f) Does not change the slip in per cent for the same h.p.
(g) Does not change the secondary copper loss in watts.
(h) Usually decreases the power factor.
(i) Usually does not materially alter the efficiency.
(j) Usually somewhat increases the heating.

The above statements are reasonably correct for a variation of not more than 10 per cent above the below rated frequency and in general operation would be satisfactory over that range.

From the foregoing table on voltage and frequency it follows that the voltage and frequency should not be allowed to vary in opposite directions at the same time, *i.e.* voltage high and frequency low or vice versa.

It also follows that if the voltage varies from normal either above or below and the frequency varies with it by the same percentage, the motor tends to develop the same torque at all times with nearly the same operating characteristics at that torque. The h.p. developed varies, of course, directly with the rev. per min.*

VARIATIONS IN PHASE

Variations in phase, as popularly considered, can occur in two ways, either by an actual variation from true phase in the phase angle or by a higher voltage existing on one or more phases than on the others. The results in either case are bad and fortunately the condition is not so apt to occur as variations in voltage and frequency. This question is treated thoroughly in a paper by Messrs. Charters and Hillebrand in the TRANSACTIONS of the A. I. E. E., Volume 28, page 559. Their conclusions are that the capacity of the motor is reduced by either of these causes and that a relatively small variation may cause serious heating. The reason for this appears from a consideration of the tendency of a polyphase induction motor to balance up the circuit to which it is connected. In order to effect this correction, balancing currents flow in the secondary having such phase and value as will tend to reduce the primary current to a balanced relation. If the system is relatively small and the motor unit large, practically entire correction may result at the expense of slightly increased heating.

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*Some interesting comparative data on the effect of voltage and frequency variations on induction motor performance are given in an article by Mr. G. B. Werner, in the *Electric Journal*, Vol. III, page 400.

But if the system is large and is unbalanced to any considerable extent the motor is unable to exert an entire corrective effect but does its maximum with resulting disastrous results. Data on the exact result of different amounts of unbalance are hard to obtain but it is not unusual for the heating to increase 40 per cent to 50 per cent when the voltage on the lowest phase divided by the voltage on the highest phase is as high as 90 per cent. The writer has experienced serious trouble from so simple a case as operating a 600-h.p. squirrel cage motor from two 300-kv-a. transformers in open delta. In this case the slight variation of the third side of the delta from its theoretically true value caused sufficient corrective current to flow in the motor to overheat it.

CONCLUSIONS

The conclusions to be drawn from the foregoing are;

(1) That 60 cycles is preponderant as a choice for frequency for general all-purpose work. For heavy slow speed work 25 cycles has advantages.

(2) That present standard voltages are satisfactory and should be employed with regard to the size of the unit and pertinent local conditions.

(3) That 3 phase is the most desirable choice for phase.

(4) That variations in voltage and frequency 10 per cent above and below normal rated values do not seriously impair operation and that if voltage and frequency vary together even greater variations than 10 per cent may be allowed.

(5) That all variations in phase caused either by phase shift or unbalanced voltages should be avoided so far as possible.

SELECTION OF MOTORS WITH REGARD TO FREQUENCY, PHASES, AND VOLTAGE

A. E. Averrett: The selection of induction motors with regard to frequency, phases, and voltage is perhaps a secondary consideration, as these points are of more importance when applied to the generating and transmission system, as well as to the motors. In fact these points should be considered from the standpoint of the entire system of electric generation, transmission, and distribution of power. However, there are characteristics of induction motors which are influenced by the frequency, phases, and voltage and some of these effects will be considered.

The most important points are as follows—*efficiency, power factor, speed, maximum torque, air gap, starting torque, starting current*, and last but not least—*cost*.

Under the head of frequency, present practise includes from 125 cycles to 15 cycles, with the general use in this country of 60 and 25 cycles, and a few 40 and 50-cycle systems; it should be sufficient therefore to consider 60 and 25 cycles as covering most cases.

For a given h.p. and speed, the efficiency of a 60-cycle motor is usually slightly better than 25-cycle, but the power factor of the lower frequency motors will usually be better.

From the standpoint of speed 60-cycle motors offer a much wider range of speed than the lower frequency, due to the larger number of poles. On 60 cycles any speed from 3600 rev. per min. down corresponding to the poles can be obtained; on 25 cycles, 1500 rev. per min. is the maximum practical speed. In the lower ranges of speed the following are the respective no-load values, 60 cycles—1800, 1200, 900, 720, 600, 514; whereas 25 cycles can only have 1500, 750, and 500, at lower speed the two ranges come nearer together.

Other things being equal the maximum torque of 60-cycle motors is less than 25-cycle motors, so that for momentary overloads the lower frequency is superior.

Since the power factor of low frequency motors is usually much better, and especially so on low speed motors, it is permissible to use a somewhat larger air gap on 25-cycle motors than on 60 cycles of the same approximate horse power and speed; this is very noticeable on motors subjected to severe mechanical shocks, where the larger air gap is necessary to give increased mechanical clearance and prevent the rotor striking the stator. As the power factor should be maintained reasonably high, if it is necessary to have large air gaps, low frequency is required; in fact in certain types of mill induction motors it has been found impractical to build a satisfactory motor for 60 cycles.

Starting torque is usually superior on 25 cycles and while the starting current is slightly higher than on 60 cycles the starting torque per ampere is nearly always better on 25 cycles than on 60 cycles.

Costs are usually higher on low frequency motors of average types because with the present types of iron it is feasible to work nearly the same magnetic density on 60 or 25 cycles, in which case the sections of iron must be approximately inversely proportional to the frequency. This larger amount of iron in turn requires a longer length per turn of copper, therefore, the weight of active iron on copper must increase very largely. As an offset the amount of labor in winding and insulation may be less, but the mechanical parts for the same stresses will have to be equal and as a net result the total cost and weight will usually be somewhat higher on 25-cycle motors than on those of 60 cycles. Since the greater number of motors sold in this country are for 60 cycles the question of quantity production at present helps for lower prices on 60-cycle motors.

NUMBER OF PHASES

There are practically only single, two, and three-phase induction motors in use and these two latter can be classed as polyphase; since the single-phase motor when running near full speed has essentially a rotating field, it is comparable to a poor polyphase motor. The single-phase maximum output is less than half with the same motor when on a polyphase circuit and, as it is not self-starting, a polyphase winding must be used in connection with a phase-splitting or equivalent device to enable the motor to start. In every way the single-phase induction motor is inferior to the polyphase. The only reason for using it is, that it requires two wires instead of three or more.

As regards two and three phase, in nearly every case a three-phase motor is superior to a two phase. The efficiency or power factor or both are superior if proper windings are used and the cost maintained the same, also the well known saving in copper of a three-phase line over a two phase applies to the motor circuits. It would seem that from the motor standpoint a three-phase motor is superior to either the two phase or single phase.

The question of voltage is largely one of cost; low voltage motors are cheaper and more efficient than moderate or high voltages in small sizes (roughly under 100 h.p., motors of 200 or 300 h.p. may well be wound for 2000 volts. Motors for 6000 volts or more should be used only in large sizes. Low voltage is much safer for the attendants.

It might be stated that low voltage motors usually give better operating characteristics but at the expense of increased line copper.

High voltage motors on the other hand save line copper but with higher motor costs, poorer operating characteristics, and increased danger of breakdowns and injury to attendants.

Unbalancing of either phases or voltage or both tends to increase the heating and reduce the break down capacity, the amount depending on the quality of the motor design constants.

In general unbalancing tends to make a polyphase induction motor act as a phase converter drawing current from a lightly loaded leg to relieve a heavily loaded circuit, but at the expense of extra heating in the motor.

H. L. Wallau: There is one point brought up by the last speaker in connection with two versus three-phase distribution.

A system installed in one part of this city, where the distribution is underground, meets the situation in this way. The territory supplied is divided into load sections normally independent, but which can be tied together through junction boxes *A*. See Fig. 2.

Each section is fed from a bank of two transformers, a 25 kw. and a 10-kw. connected in open delta, and located in the middle of the section.

The secondary of the larger transformer is connected 115/230-volt, three-wire, that of the smaller transformer connected so as to give three-phase service in connection with the outer wires of the larger transformer.

The distribution system thus consists of a three-wire lighting secondary and a fourth or teaser wire.

The leads from the transformers are connected to the low-tension mains through four-wire junction boxes *B*.

Successive large transformer units are connected respectively across phases *a-b*, *b-c*, *c-a*, etc., the teaser units being connected across phases *b-c*, *c-a*, *a-b*, etc., thus maintaining practically a balanced load on the primary line.

In case of failure of any transformer bank, all the fuses in the corresponding box *B* are pulled, thus breaking this section into two half-sections independent of one another. The fuses in the boxes A between these two half-sections and the adjacent regular sections are then closed, when each of these adjacent sections picks up half of the load of the section on which the trouble occurred. The neutral wires are unchanged and phase rotation remains unchanged.

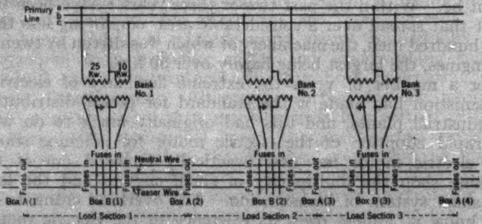
Primary Line
a
b
c
25 Kw.
10 Kw.
Bank No. 1
Bank No. 2
Bank No. 3
Fuses in
Fuses in
Fuses in
Neutral Wire
Teaser Wire
Fuses out
Fuses in
Fuses in
Fuses out
Fuses in
Fuses in
Fuses out
Fuses in
Fuses in
Fuses out
Box A (1
Box B (1)
Box A (2)
Box B (2)
Box A (3)
Box B (3)
Box A (4)
Load Section 1
Load Section 2
Load Section 3

FIG. 2—3-WIRE SINGLE-PHASE 115-230-VOLT SECONDARY WITH FOURTH OR TEASER WIRE FOR THREE-PHASE 230-VOLT SERVICE—NORMAL CONNECTIONS. IN CASE OF FAILURE OF ANY BANK, SAY NO. 2, ALL FUSES IN BOX *B* (2) ARE REMOVED AND FUSES IN BOXES *A* (2) AND *A* (3) ARE INSTALLED—NEUTRAL MUST BE CLOSED BEFORE CLOSING 230-VOLT LINES IN ANY *A* BOX.

INDIVIDUAL VERSUS GROUP DRIVE MACHINE TOOLS

C. Fair: The advantages of the electric drive in industrial plants in general are well known and its importance in relationship to production is becoming better understood each year; yet there is much which is still imperfectly understood because of conditions which are constantly changing and because of vast improvements in electrical machinery. For these reasons it is difficult for one, who is not continually in touch with the situation, to keep abreast of the times.

Originally, lighting was the principal, if not the only, advantage claimed for electricity. Little was known of shop equipments as we now see them. The first few motor drives were scattered and confined practically to line shaft drives and to a few portable drills with flexible shafts. The individual motor-driven machine tool was about as much of a curiosity then as an individually steam engine driven machine tool is today. As the motor began to replace the numerous engines scattered about the shops and to break up the long mechanical transmission lines, a great saving in power and improvement in continuity of service were noticed.

It was during this period that many of the claims of saving in power were made that now appear rather extravagant. It will be seen how enormous were the power losses when one considers that steam was often transmitted to numerous engines for long distances, from one or more power stations through small and often uncovered pipes; or else the power was distributed by long shafts transmitting power from one building to another or from one shaft to another, around corners by quarter turned belts and to various floors, etc. Much of this shafting was in very bad alignment. When the long shaft or any part of the long transmission system was broken, it often tied up a large part of the plant until key-ways could be cut and the shafts recoupled or a section of the shaft replaced, or the belts repaired, as the case might be. Within the past two or three years I have been in a plant that spread over a considerable area, employing less than four hundred men, the machinery of which was driven by twenty-six engines, the largest being hardly over 50 h.p.

For a number of years the extreme flexibility of electrical transmission has made it the standard for power distribution in industrial plants, and this had originally much to do with the rapid adoption of the electric motor for machine shops. The electric motor has now practically crowded out of the machine shop the multiplicity of small engines and the long line shaft system of transmission. The overhead crane, as we now know it, almost owes its existence to the electric motor, the cumbersome mechanical transmission having some time ago passed into oblivion. Aside from the comparatively few portable machines, the largest machines were generally the first to be individually motor driven. With the coming of the adjustable speed motor and later the high speed steels, the future drive for the progressive machine shop is no longer one of speculation.

Today the important questions before the manufacturer are how to increase production and how to decrease cost. In the majority of cases labor is the greatest cost of production. Thus where machine tools are a considerable factor in the production and where labor is one of the principal items in the cost of production, the importance of obtaining a maximum output from the tool is evident. Tools that are limited in their productiveness because of the lack of power at the tool are a source of expense to the manufacturer, not only on this account but on account of the excessive labor due to the additional time required. The power cost of production is comparatively small, roughly varying from one to three per cent, while the labor cost is usually a very large item of the production cost, often amounting to fifty per cent and upward. If, therefore, by increasing the power on a given tool its output can be increased, the conclusion is obvious.

If the plant under consideration be very small and the machines only of fair size, local power conditions might be the deciding factor in the motor applications, and as the current available for the smaller shop would generally be alternating current, the machines would so far as possible be selected to fit this condition. The very size and product of the small factory make a desirable layout a comparatively simple matter and especially is this true where cost does not warrant the necessary outlay to obtain the increased production.

The question of using alternating versus direct current or both, would, to a large extent be decided by the size of the plant, the nature of the work, present installation, if any, proportion of constant to adjustable speed drives, etc. If the shops covered considerable area, it might pay to generate alternating current for convenience of transmission and convert the necessary direct current. Again it might be advisable to generate both alternating and direct current.

Large industrial plants, using many individually driven machine tools including metal and woodworking machines, would operate advantageously with both alternating current and direct current. Alternating current for the majority of the constant speed type machines including certain of the machines with mechanical speed changes as drill presses and certain types of lathes, shapers, etc., wood working machines, group drives, and constant speed auxiliaries, lighting and to a certain extent transmission, etc.; direct current for all adjustable speed machines and for machines, the duty cycle of which can best be taken care of by the d-c. motor.

The choice of constant speed motor drives in combination with the all geared speed change machine versus the adjustable speed motor driven machine depends largely upon the kind of machines under consideration, and upon the work; for instance, on all geared head lathes turning only straight away work, such as axles, shafts, etc., the constant speed motor would be satisfactory, but for work constantly changing in diameter or for facing and boring operations, or where the work must be stopped many times for callipering or fits, or for running off small cuts rapidly until the heavier cut is met or for cutting up against shoulder, etc., the d-c. adjustable speed motor has all the advantage. Not only can the speeds be instantly and conveniently changed when wanted, but the machine can be quickly stopped by means of dynamic braking. In the case of automatics, semi-automatic machines, etc. the motor speeds can, of course, be easily changed automatically. There are in fact hundreds of cases where production can materially be increased by the use of adjustable speed motors. The direct-connected, reversing d-c. motor-driven planer is another example of increased production due to adjustable speed motor and to the flexibility of the control. The properly combined unit of machines, adjustable speed motor and control can be made to accomplish much toward increasing production.

Some of the advantages claimed for the direct-connected tool are as follows: Maximum output of the tool due to greater power and overload capacity, absence of slipping belts, closer speed regulation which allows a maximum cutting speed for metals of varying degrees of hardness, rapid speed changes, quick starts, stops, reversals, independent operation of auxiliaries and ease of manipulation through convenient control stations.

Elasticity in the arrangement of tools: Tools can be arranged to the greatest advantage for sequence of operation in routing work, and also for good lighting as well as for compactness when necessary.

Ease of adding new tools and of moving and rearranging tools: Ease of adding new tools means a great deal in growing plants. Rearrangement becomes necessary after reasonable growth or because improvements in methods of manufacture call for a better routing of work.

Head room for cranes, hoists, etc. For example, note the expensive manner in which work is often handled because belts or shafting interfere with the installation of cranes or hoists.

Facility for running only such tools as are required for overtime work.

To a large extent the elimination of belts and belt troubles.

Safety to operators: The individual motor drive offers absolute protection to the operator from accidental starting up of the machine by merely opening a switch. Machines so protected cannot be started unexpectedly by the starting up of line shaft, the creeping of belts from loose to tight pulley, the sticking of clutches, etc., or by the accidental tripping of clutches by the operator. This additional safety is of particular advantage on machines requiring certain setting up operations, as on punch presses, etc., also by the fact that machines can be quickly stopped from any one of a number of the motor control stations.

Some of the indirect advantages are: Power distribution not only for tools, stationary or portable, but for lights, cranes, elevators, furnaces, welders, transportation, etc. Power and light can be had quickly and cheaply in any part of the buildings or yard, permanent or temporary without regard to structural conditions.

Unobstructed light and sanitation: Numerous belts obstruct light, whether natural or artificial.

Competition today necessarily means the monotonous duplicate system of manufacturing wherein the individual makes only one part of the finished product. It is now recognized as not only desirable but as an economy that some form of interest be restored to help break this monotonous routine of duplicate manufacturing. This can and is being accomplished in a manner by making the surroundings attractive. Individual drive not only increases production, but reduces to a minimum many of the unattractive features of the shop, such as overhead revolving pulleys, masses of moving belts, noisy transmission, stirring up of oil and dust, and bad lighting conditions. Electric drive also reduces many heavy manual operations to a minimum by the use of auxiliaries. It pays to capitalize cheerful surroundings.

The general use of high-speed steel has made it not only possible but necessary for economical production, that the cutting speed be increased in order to meet competition. Increasing the cutting speed naturally means more power; and while much has been said from time to time regarding the increased production and saving in power due to applying the power direct to the tool, yet the writer has very serious doubts if anything like the real importance of this direct application of power is realized in many cases, even by those who are advocating it. For instance, the saving of power is looked upon generally as a matter of how much of the transmission friction load can be saved, and, though this saving may amount to 50 per cent, it is in many cases only a part of the real saving as has been proved by numerous tests made by the writer.

The slipping, due to a belt not being able to pull its cut, means waste power and loss of production. If the cut be heavy enough the maximum slip will be reached when the machine is stalled, the power input remaining approximately the same. The load is now entirely one of friction due to slip in the belt. A familiar illustration of this fact is that of an operator decreasing the depth of his cut on account of the slow down, because the belt will not carry the load. The solution of this would seem to be increase the size of the belts. This will suffice in some cases, but there are numerous instances where either there is not room to increase the width of the belt or if step cones be used the number of steps will have to be decreased. Such means as multiple countershafts or additional gearing must be included to complete the speed range. Furthermore, it is difficult to shift large belts, and this method generally results in much loss of productive time.

As previously mentioned, up to a few years ago in the majority of shops where motors were used they were usually belted to the line shaft or the countershaft of the tool. Adjustable speed motors were not so commonly used then as now, nor were they made in the great variety of sizes and speeds now obtainable. Today, especially in the case of new tools with their requirements of high power and close speed regulation, it becomes not only more convenient, but in many cases almost a necessity, to apply the motor directly to the tool.

In driving tools with individual motors it will be noted that the motor not only supplies the power and speeds best adapted to the tool, but that in the case of variable speed tools the speed range of the adjustable speed motor alone will, in many cases, cover the entire speed range of the tool. The motor and its controlling apparatus should, whenever possible, be connected directly to the tool, thus making a compact unit, which has also the additional advantage of allowing the entire machine to be moved by simply disconnecting the leads and connecting them in the new position In the case of protable tools, this, of course, is an absolute necessity.

The advantages of individual motor drive for large tools and for certain of the smaller tools have been conceded for years, but there are many tools where either the cost of the motor or the cost of applying the motor to the tool is prohibitive on account of the construction of the machine. This cost could be modified by making the motor a part of the tool rather than a mere addition to it.

Better drives are possible now than formerly, due to the greater motor speed range obtainable, to the decrease in size of motor per horse power, to motor characteristics which specially adapt them to the work which they are to do, to more perfect balance of the rotating parts at high speed; and, to a certain degree, to improvements in gears which allow higher speeds without excessive vibration and noise, and to the many recent improvements in control.

Considerable difference of opinion has developed as to the advantages of individual versus group drive, and while it is generally agreed that it is advantageous to have the larger tools individually driven, the agreement by no means extends to the smaller ones. Under certain conditions there is no question as to the advantages of the individual drive for small tools, as, for example, where small tools are necessarily placed among larger ones, or to allow convenience in the placing of tools in the assembling departments, etc.

There are naturally many machines working under conditions that would not justify the outlay necessary for driving them by individual motors and these machines should be grouped and driven by a single motor per group. When the work of actually equipping a factory with motor drive is undertaken, it is necessary to study the conditions of operation, which vary greatly with the product manufactured. The arrangement of a factory may be entirely different if many motors instead of a few groups are used. Simply the difference in the position of a number of the tools may greatly facilitate the handling of material.

When direct connected drives are to be installed in a new building, a substantial saving in the actual cost of the building can be made by omitting the necessary reinforcements, inserts or provisions that are usually made (depending on the construction of the building) for carrying the line shaft and numerous countershafts. This saving, together with the cost of line-shafts, counter-shafts, hangers, pulleys, clutches, belts, etc., should be taken into consideration when figuring the cost of the electrical installation.

In conclusion, we cannot help but call attention to the greatly increasing number of individually motor driven tools which is due primarily to the fact, as has been shown, that the tool so equipped can do more work, can do it better, and do it cheaper.

FACTORS INVOLVED IN MOTOR APPLICATION

R. W. Davis: The following remarks upon the effect on motors of frequency, phase, and voltage are based upon induction motor applications, since this type of motor predominates in commercial drives and is continually becoming more and more important with the increase in development of alternating-current power.

The frequency to be employed is fixed by considerations entirely independent of the motor application in the majority of cases. The small power user generally buys power from a public service company and must adopt the frequency available, usually 60 or 25 cycles. In a few special applications, as, for example, driving machine tools, the flexibility of speed control warrants the installation of a motor generator set and direct-current motor drive. Large users of power frequently have their own generating plants and can exercise more or less choice in the selection of frequency. Even then some consideration must be given to the frequency supplied by the neighboring power company, for in case of serious damage to the power plant, it might be desirable to obtain temporary service from the electric company. If the frequencies are the same, the most that will be needed will be a set of transformers; while if the frequencies are different, a frequency changer must be installed with possibly transformers in addition.

Assuming that the amount of power required or local conditions are such that the power user is free to fix upon a frequency entirely independent of the public service company, the choice of frequency is dependent upon the service. Where very low speeds and large overload capacities are required, as in rolling mill service, a frequency of 25 cycles should be employed; for the efficiency, power factor and overload capacities of a 25-cycle induction motor are inherently good. The 25-cycle motor really lends itself to the heavy rugged construction required by steel mill service.

The 60-cycle motor has approximately the same efficiency as the 25-cycle machine, but poorer power factor and lower overload capacity for a given rating and speed, and is usually a lighter and cheaper machine. A number of installations have been made with a frequency of 40 cycles and have given excellent service. The efficiency is about the same as for 25 or 60 cycles and while the power factor and overload capacity are lower than for a 25-cycle machine, they are much better than in a similar 60-cycle motor and compensate for the slightly greater cost. Forty-cycle motors can be built with good power factor and relatively large air gaps. Motor purchasers often fail to pay sufficient attention to power factor and air gap and consider power factor only from the dollars and cents point of view of supplying current to the motor. The power factor of an induction motor is almost directly proportional to the radial length of air gap, and the motor with the large air gap, though possibly costing slightly more for power, is much more reliable and will save enough in repairs, operator's time and fewer shut-downs to make up the difference in power cost many times over. In continuous operations a single shut-down will frequently cause a loss several times greater than the original purchase price of the motor.

The speed obtainable with the different frequencies is an important item, and in this respect the higher frequencies have a very decided advantage. With 25 cycles the higher synchronous speeds are limited to the following; 1500, 750, 375, 300, rev. per. min. while with sixty cycles the corresponding speeds are 1800, 1200, 900, 720, 600, 514, 450, 400, 360, 327 and 300 rev. per min. These include the 25-cycle speeds with the exception of 1500 rev. per min. and in addition the important speeds of 1800, 1200, 900, 600 and 450 rev. per min. which are not available with a 25-cycle system.

The number of phases is frequently determined by the power supply available and is not open to choice. Three-phase power should be used for motor drive wherever possible since the characteristics of a three-phase induction motor are much better than those of a two-phase machine.

The choice of voltage is dependent upon a number of factors, and the voltage adopted should be that one which will give the best average service, due consideration being given to the cost of motor, switches, lines, transformers, general reliability, etc. Considering this from the motor standpoint, we find that the percentage of slot area taken up by the insulation is a very important factor and is more or less dependent upon the size and speed of the motor. Induction motors differ from synchronous machines in that they require more slots per pole to give satisfactory operation, and the percentage of total slot space taken up by the insulation is therefore greater. As the size of the motor increases, the slot pitch usually becomes greater, permitting the use of wider and deeper slots. The number of slots increases with decrease in synchronous speed for a given horse power and frequency. Hence speed as well as the horse power of the motor should be considered when selecting the voltage. On account of this, small motors, say up to about 50-h.p. capacity, and medium size slow speed motors, should be wound for 550 volts or lower. A voltage of 2200 is satisfactory for medium size standard speed motors and all large machines.

Conditions are such in many cases that it is desirable to wind the motors for a voltage higher than 2200. This is practicable where the amount of power per unit is large. There are a large number of induction motors wound for 6600 volts which have been in operation for a number of years and which have given entire satisfaction. A very few induction motors have been wound for service on 12,000 to 13,200-volt lines. These voltages require a very large number of turns per coil, and even in the largest machines a considerable portion of the slot space is taken up by insulation. Motors of this character are liable to be broken down between turns inside the coil by line surges caused by high-tension switching. It seems very questionable to the writer whether it is desirable to wind any induction motor for higher than 6600 volts.

The small variations of voltage and frequency such as are usually met with in ordinary commercial service do not have any material effect upon a standard 40-deg. cent. induction motor. By this I mean that the motor will continue to carry its load without overheating. The adoption of a 50-deg. cent. maximum rating as a standard may require closer regulation of the power supply. The materials in these machines will be worked harder and there will be a somewhat smaller factor of safety than with the normally rated motors, hence the effects of deviation of frequency and voltage from normal will probably be more appreciable.

GROUP VS. INDIVIDUAL ELECTRIC DRIVE

H. R. Johnson: There is perhaps no phase of the problem of applying electric motors to factory drive, involving a greater number of debatable points than that of the choice between individual or group drive. For this reason little more can be attempted in a short discussion than to outline the more important determining factors. Generally speaking, it may be said that properly planned individual motor drive always realizes in the highest possible degree all the manifold operating advantages of electrical power distribution and application.

Group drive still has, and always will have, a field of usefulness in which it is superior, all things considered, to the method of individual motor drive. Nevertheless, results obtained in comparison with the best methods of group drive show that, when a company can afford the initial cost of separate motors, their use generally results to the greatest ultimate economy, as well as convenience.

Probably the most important advantage of individual drive is the possibility of increased production. This increase may result from a number of different causes and ranges in amount from the moderate gain due to greater reliability and fewer interruptions with ordinary constant speed machines, to the tremendous increase in capacity achieved with some of our most modern machine tools with automatic or semi-automatic electrical control and precise speed adjustment for both cut and feed.

Adjustable or multi-speed motors with ordinary hand control net a very considerable saving in time required to effect speed adjustments, as compared with mechanical arrangements involving cone pulleys or gear changes; this advantage is further accentuated by the ready practicability with which simple control levers can be placed convenient to the operator's hand, while remaining in a position to closely observe the work being done, thus increasing production not only directly but also indirectly by reason of finer control of operations and consequent smaller percentage of outages.

In line shaft (or group) drive, every successive belt through which power is transmitted from the primary source to the tool itself gives a drop in speed of 2 to 3 per cent (often more) which may in some cases result in a serious reduction of speed at the tool or, if the load is variable, an annoying speed pulsation. On some very fine work, such as textile loom drive, the more precise speed maintained by individual motors actually improves the quality of manufactured goods, as well as increasing production by at least three or four per cent. With improved modern tool steels it is often desirable to increase the speed and depth of cut of old belt driven machines. In such cases considerable trouble is often experienced with slipping belts, while in occasional instances the allowable size of belt and pulley simply will not satisfactorily transmit the required power. Fortunately it is generally possible to mount an individual motor on the machine frame and to effect a positive gear drive.

The readiness with which the most elaborate controls can be accomplished electrically, brings very important time saving possibilities within the reach of such industries as those of cloth and newspaper printing. Not only is delicate and positive speed adjustment made possible, without the use of cumbersome mechanical devices; but more important still from a productive standpoint, a great deal of time is saved in preliminary or make-ready operations, by means of extremely low obtainable speeds and "jogging" features.

Specific examples in which individual electric drive makes possible small or large increase in productive capacity or saving in time, which amounts to the same thing, could be multiplied almost indefinitely. We believe that almost any machine which requires operating speed adjustments, and many others besides, can be made to produce from 5 to 50 per cent more with individual motor than with group or shaft drive.

Probably next in importance to increase of production is the power saving with individual drives. It must be admitted that even with properly planned group drive a good deal of the friction load will not have been eliminated. Although main line shafting and belting may have been eliminated, there still remains, practically the same, or an equivalent, system of secondary belting or countershafting. It is seldom indeed, even in the best examples in practise, that groups are laid out to avoid "idling" of a large proportion of the driven machines. In general machine shop work, for example, the percentage of machines momentarily idle at any given time may run as high as 60 per cent. Wherever such operating conditions obtain the use of individual motors, whose power demand ceases the instant the driven machines are shut down usually results in a power saving of 10 to 50 per cent and frequently more.

Opposed to the possible increase of production and salvage of wasted power accomplished by individual drive is the increased initial cost. The point is well illustrated by the accompanying curve, Fig. 3, showing the rapid increase in cost of motor equipment when composed of small units. The figures are drawn from actual retail prices for constant speed d-c. motors with pulley and sliding base, speeds chosen being in the neighborhood of 1100 revolutions per minute for small sizes and about 700 revolutions per minute for larger units, *i.e.*, speeds somewhat lower than the practicable limit for belted drive. The comparison in practise would be still more striking since belted motors driving shafting could often be chosen at higher speeds, while geared individual motors would often need to run at a slower rate. Furthermore, in order to realize one of the principal objects of individual drive, the smaller motor might need to be of the adjustable speed type and hence involve a higher initial expense.

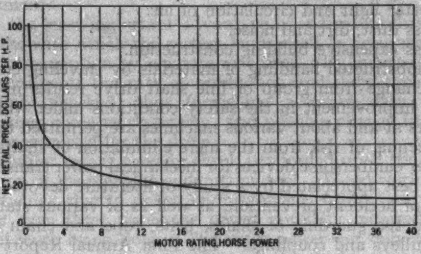

Fig. 3

Considering any rational possible saving in first cost of shafting, hangers, etc., when using individual drive, this cost would be largely offset by the expense of installing the greater number of motors, involving as it would in many cases necessary alterations in the mechanism of the driven machine as well as the construction of supporting brackets, extra conduit work for wiring and possibly the charge for expert designing and drafting.

It will readily be seen, therefore, that to justify the extra cost of individual drive, the material advantages gained must be in proportion. The investment is amply justified by any appreciable increase in production. In general, the cost of power and fuel is only 2.5 to 3.0 per cent of the value added or created in manufacturing processes, as shown by the U. S. Census of

Mfg. Industries, while the wages (exclusive of clerks and salaried help) is practically six times that amount. A glance at these figures shows precisely why, almost regardless of the running or investment charges on the motive equipment, a large majority of manufacturing plants profit very substantially by the use of individual drive. An apparently small increase of production will amply justify a large percentage increase in the cost of power, since the latter is always a very small element in total cost of production.

Besides the points already discussed there are a multitude of by no means unimportant advantages attendant on the use of individual drive, any one of which may prove determining factors in making the proper choice; these features all have a more or less direct result in increasing production or improving the quality of the manufactured goods. For example, individual drive makes possible a shop whose overhead space is unobstructed by shafting, pulleys and belts, thus permitting:

1. Better light and circulation of air.
2. Less dust, dirt and noise.
3. Less expensive building construction.
4. Unobstructed handling of materials by traveling cranes.

The change from group or line shaft drive results in a substantial improvement in the safety conditions under which the operators at and about various machines are permitted to work. The lessening of risk from the mere elimination of shafts, belts and other cumbersome devices for mechanical power transmission may be best appreciated by a study of literature devoted to the subject of accident prevention, as well as of various state laws requiring the guarding of shafts, belts, rope and chain drives, gears, pulleys and couplings. The First Annual Report of the Massachusetts Industrial Accident Board, 1914, shows 3.6 per cent of fatal, and 2.75 per cent of non-fatal accidents to be due to belting, gears, shafting, set-screws, couplings, etc. In addition "falls", which present a formidable total, are undoubtedly contributed to by the presence of mechanical power transmitting devices.

After all, individual drive gains its strongest claim as a promoter of personal safety because of the ease of control over ordinary operations, the possibility it offers of perfecting at a reasonable cost, the most elaborate automatic controls for special operations, or centralized controls for intricate and extensive machinery systems which should be operated as a unit; in addition to the ease with which automatic stop buttons and levers can be arranged at points convenient to any one of several operators or attendants at a single machine, or at points where hazardous operations are to be performed. Examples of such accident saving control features might be multiplied without end, did space permit.

Individual motor drive, by merely opening a switch, offers absolute protection against accidental starting of machinery.

All danger of such an occurrence due to the unexpected starting up of line shafting, the creeping of belts from tight to loose pulleys, sticking or accidental tripping of clutches is at once eliminated.

The reduction of nervous strain and the beneficial effect on precision of movement and keenness of the sight and hearing due to improved lighting and ventilation with reduction of noise, dirt, dust and delays resulting from the change to individual motor drive are important indirect contributors to the cause of accident prevention.

Another very important point is the ideal freedom allowed in arranging machinery, without reference to the location of shafting and with an eye single to the most advantageous handling and routing of goods in the manufacturing process, to space economy, rearrangements, enlargements, etc.

Individual drive provides insurance against serious interruptions of production due to failure of any one motor, since the difficulty affects only one machine instead of an entire group or department.

Not the least important advantage of individual drive is the readiness with which the system lends itself to accurate tests of power consumption by separate machines. By means of recording instruments the rate of production and duty cycle can be accurately checked, thus furnishing accurate data for cost accounting, piece work pricing, and possible change in the size of the motor used for the drive.

By similar means a ready check is afforded upon the physical condition of the machine and cutting tool. Wood-working tools in particular, due to dulled or misaligned cutters, may absorb two or even three times the power normally required for the kind of work being done. The extra power not only is wasted but is liable to react injuriously upon the machine itself by way of strained parts or heated bearings. By systematic occasional readings of power consumed while running light and loaded, faults may be found and corrected before serious loss or trouble occurs. This particular phase of the subject is likely to attract much more attention in the future than in the past.

Conditions that point strongly to group drive as the proper choice are:

1. Groups of constant speed machines which may be arranged to run continuously, or simultaneously.

2. Compact groups (*i.e.*, those requiring only short lengths of countershaft) where, due to the diversity factor in operation, the h.p. rating of a single motor to drive all machines together may be considerably less than the combined h.p. necessary to equip all with individual motors. (This is especially true when motor rating is less than 2 h.p. each.)

In neither of the above cases could the power consumption be greatly reduced by individual drive nor, since only constant operating speeds are required, would the increase in production be more than a nominal amount.

3. Groups of similar constant-speed machines which, due to extra heavy starting demands or momentary peak load requirements, would require motors for individual drive considerably in excess of the average running load.

4. Groups of very small machines where, despite some saving in power, individual motors would be unreasonably costly and inherently somewhat less rugged and reliable than larger sizes.

Any considerable increase of production would, however, justify individual motors in such a case.

To summarize, the only practical disadvantages of individual drive are higher first cost of equipment and, in the case of very small motors (fractional h.p. sizes) a slight inherent reduction in ruggedness and reliability. Among the advantages to be gained are:

1. Increased production.
2. Saving of power.
3. Possible improvements in arrangement of machinery, saving in cost of millwrighting, and building construction, free overhead space, better light and air, increased safety, etc., which may be grouped under the heading of "attendant advantages."

The ultimate choice will depend in any case upon the importance attaching to the various factors with reference to the particular factory conditions to be met, affected to some extent by the tastes and preferences of the customer's personal representative.

SAFETY FIRST IN MOTOR APPLICATIONS

W. C. Yates: People not fully informed might infer, from the present widespread attention that is being paid to ways and means of safeguarding workmen from accidental injury, that practically no thought had hitherto been given to an obviously most important matter. Such is not the case, as anyone who cares to investigate can readily learn. It is not proposed to discuss here the reasons for the awakened general interest in the movement which has for its slogan "Safety First." Our subject deals with motor applications, and it will be noted that many of the precautionary measures advocated in the following have been in force for some time. The really new ideas, as represented in certain recently designed motors and controlling devices, also by installation features of novel character, indicate that the latest steps are toward protecting the operator, electrician, cleaner, repairer, or anyone who may for reason or no reason, handle or tamper with the equipment, against any grievous results of carelessness, negligence or ignorance. There have been for many years safeguards adequate for an intelligent workman exercising a reasonable amount of care.

The field of application of the electric motor constantly broadens and becomes more diversified. In these days it is out of the question, perhaps even undesirable, to place the operation of all motors in skilled and intelligent hands. Much motor-driven machinery is operated by men whose knowledge of mechanics and electricity is absolutely nil. It is necessary to protect each against the other, and " Safety First " concerns the protection of the man.

Safety First in motor applications could be considered to embrace precautions taken in the whole system of which the motor is a part; including the power plant, transmission, transformers, internal wiring, etc. on one hand, and the safeguards placed on the driven machine on the other. This discussion will be confined to the motor and its control, beginning with the leads supplying power, and ending at the pulley, pinion, clutch or coupling through which the motor transmits power to the machine.

THE MOTOR

Wiring to the Motor: The danger here is one of electric shock and can be guarded against by:

1. Bringing the line leads through conduit to a conduit box enclosing the motor terminals. The conduit should be electrically connected to the motor frame. Up to date types of motors, having terminals mounted upon terminal boards, are designed to receive standard conduit fixtures for enclosing the terminals.

2. Bringing the motor leads through bushings in the frame and using thoroughly insulated and protected connectors for connecting to the line leads.

3. Placing the motor out of reach or in a pit with the terminals under the motor.

There are, of course, special cases which demand special treatment. For instance, crane trolleys must of necessity be bare and should be suitably guarded and danger signs erected where workmen may have occasion to come in close proximity to the wires.

The Motor. The motor offers possibilities of both electric shock and mechanical injury. The guarding of the terminals has already been referred to. In addition:

1. The frames of all motors operating on high voltages, such as 2300 should, without question, be permanently and effectively grounded. Grounding of the frame is also essential on lower voltages in installations where dampness, acid fumes, or other deteriorating agencies can affect the insulation.

The question is still open as to the advisability of grounding motor frames as a general practise on the lower voltages. The A. I. E. E. Standardization Rules demand high potential tests, which are amply sufficient to ensure improbability of the motor windings grounding. It should be borne in mind, however, that insulation deteriorates with time, and after several years service it is not reasonable to suppose that the same factor of safety exists. It is best to be on the safe side, and to be absolutely so it might be well to ground motor frames on all circuits of 250 volts and higher.

2. In the design of motors the tendency in the frame design is properly toward so enclosing the rotating parts that injuries caused by the rotating armature and ventilating fan cannot occur. Sufficient ventilation is provided by perforated strips or sections of coarse mesh set into the bearing heads, or by providing for the flow of air around the bearing housing.

Motors, not so protected, should be so located or guarded by a rail or shield as to make it impossible for the hand, any other part of the body, or the clothing of anyone to be accidently caught.

3. Gears, pulleys, couplings, slotted shafts and all other rotating parts should also be so shielded as to make accidental contact with them impossible. In the case of back geared motors the motor manufacturer should supply a proper gear case or guard, unless it is known that the complete machinery, of which the motor is a part, makes such provision.

It should not be overlooked in the case of motors made with shaft extensions at both ends, and where but one extension is in use, to guard the other shaft end. Some types of motors are manufactured as standard with a shaft extension for a solenoid brake, whether the latter is used or not. Where the brake is not furnished with the motor, the manufacturer should provide a suitable shield to cover the superfluous shaft extension.

THE CONTROL EQUIPMENT

The features essential to a safe control equipment may be grouped under headings as taken up in the following:

Protection from Electric Shock or Burns. It is naturally impossible to treat the control like the motor, as the former must, in the great majority of installations, be manually operated directly or indirectly. Similar considerations, however, apply to the guarding of terminals and connecting leads, and to the grounding of enclosing case and conduit.

In general, protection of the control equipment can be afforded by resorting to one or more of the following four classes:

Class (A) Protection. Out of reach, at least 6 feet, six inches above the floor level.

Class (B) Protection. Mechanically enclosed, but necessary to open doors or covers to operate.

Class (C) Protection. Mechanically enclosed, but not necessary to open doors or covers to operate.

Class (D) Protection. Protected by guard rail.

Under class (A) may be grouped either electrically or mechanically remotely controlled switches, circuit breakers, contactors, rheostats, and any other devices which are indirectly operated and may therefore be located out of reach. Automatic starters for pumps, controlled by a float switch or a pressure switch, belong in the same category. In all such cases a disconnecting switch should be installed so that an authorized person may be able to make the control dead while doing any work upon it. These same remotely controlled appliances may naturally, if desired, be protected in accordance with Classes B, C or D.

Under Class (B) may be grouped control equipments infrequently operated, and then only by an experienced and dependable operator. Starters and speed regulators for continuously running motors may be properly thus protected.

Class (C) comprises all control devices liable to frequent handling, such as drum controllers, master controllers, push-button switches, auto-starters, and other types of motor starting or regulating switch mechanisms used with motors put to service which demand more than occasional starting or speed regulation. Such service embraces shop tools, cranes, printing presses, textile machines and the like.

In Class (D) may be placed control equipment for group drive, large motors or for other such service as requires infrequent starting or stopping, and may be isolated from machinery around which men are at work. Examples of such installations are motor driven compressors, fans, conveyors, etc.

Where the replacement of fuses is left to workmen who are not experienced electricians, provision should be made to so cover the fuses that the cover cannot be removed without first opening the line switch, or else to provide an insulated fuse holder by means of which the fuse may be withdrawn from its clips and a new one inserted with no possibility of the hand coming in contact with any live parts.

Circuit-rupturing parts should be so shielded or enclosed that any arcing cannot injure the person operating the control equipment.

Protection from Mechanical Injury. Controlling devices in themselves offer little likelihood of injury other than electric shock or burn. There are, however, possibilities of injury from the motor-driven machine that must be taken into consideration. No-voltage protection is essential in all installations in which, when power has failed, the resumption of power causing the machinery to unexpectedly start would be liable to harm anyone who might be at work about the machine. When the power goes off it should be possible only for the operator to restart the motor.

In the case of any machine, such as a newspaper press, which may be operated by an automatic starter controlled from more than one control station, a safety switch should be installed at each station which may be opened at any station to prevent the starting of the motor from any other station.

Provision should be made for the locking against operation of controlling appliances of machinery on which anyone may be working not in full sight of any one else who might manipulate the controller to start the motor.

Limit switches, stopping the motor independently of the operator, are essential to safety on machinery such as hoists, where overtravel would result in damage.

It is essential to install suitable brakes on cranes or other machinery which upon failure of voltage or other opening of the circuit will prevent a descending load or continued running of the machinery from causing damage. Safe braking depends upon the nature of the installation. Best practise provides a crane either with one mechanical load brake and one solenoid brake, or else with dynamic brake and two solenoid brakes. A crane control equipment should also include, mounted within ready reach of the operator, a switch the operating knob of which may be quickly struck by the operator to open the circuit to all motors on the crane. Many machine tools require dynamic brake protection which should be provided wherever an emergency stop would ever be necessary to prevent damage.

Passenger-carrying hoists and elevators demand extra protective features peculiar to such service, and need not be dealt with in this discussion.

In General: Controlling appliances should contain only such circuit manipulating devices as will clearly indicate whether they are closed or open.

All controlling devices and equipments should be clearly marked to indicate the use for which they are intended and all terminals should be marked so as to make proper connections, a matter of no difficulty.

Controlling appliances should be made, as far as possible, so that in case of failure of any part of the mechanism the results will not be dangerous.

When installed under conditions where gas or combustible flyings may accumulate, controlling devices should be effectively closed to prevent explosions.

In conclusion it may be in order to make a plea for the maintenance of the full significance of the term "Safety First," which should not be used in the advertising or exploitation of any device or equipment that does not actually conform to all reasonable requirements. There is danger that, if used too generally or inappropriately, this trademark of protection to life and limb may be perverted by the careless, and become meaningless.

CAPACITY AND TYPE OF MOTOR WHICH MAY BE THROWN ON OR USED ON SYSTEMS, FROM THE STANDPOINT OF CENTRAL STATION COMPANIES

R. F. Schuchardt: Central stations, being in business to supply electrical service to everybody who has need for it, would naturally prefer to run "wide open"; that is, to have no restrictions whatever on what may be connected to the system, in order to make it simple and easy for consumers to receive service. Unfortunately, however, such absence of limitations would bring about conditions which would greatly impair the quality of the service rendered, not only to the consumer having undesirable apparatus but to all others on the same circuit. There are also other limitations prompted by commercial considerations; that is, by the cost of furnishing the service compared with the probable income to be derived from same. In this latter class belongs the rule which requires that all alternating-current motors of less than 5 or 7½ h.p. shall be single-phase, since the cost for the extra transformer, etc., would make a polyphase installation for this small load unremunerative.

The principal limitations imposed to safeguard the quality of the service are with respect to size of motor permitted on one side of a 3-wire system and the starting current permitted for various sizes. It is usual to forbid motors larger than ¾ h.p. to be connected on one side of a 3-wire system. With regard to the starting current, it is preferable to state this in amperes rather than in multiple of rated current since the latter method would tend to favor an inefficient motor. Starting devices are usually required on motors of 5 h.p. and larger where the installation consists of a single motor of this size. It is customary to require a power factor of not less than 80 per cent for full load condition of the motor. With low speed motors it is usual to change this requirement to 75 per cent.

The above, of course, is designed to prevent serious fluctuations of lighting pressure when the motor is started and while it is in operation. A much larger fluctuation is permitted on motors which are started infrequently than on motors which must be started very often, such as for coffee mills, meat grinders, electric pianos, and the like. Such frequently started motors are often required to be wound for 220 volts when used on 3-wire systems, since the disturbing effect is then only one-fourth as great as at 110 volts.

There is one other limitation or rather requirement which does not come under either of the two classes above mentioned and that is with respect to safety precautions in special cases. In this class comes the requirement now quite general for reverse phase relays and circuit breakers on elevator installations, cranes and the like. In general the Underwriters' rules cover this department quite fully.

It is quite possible that practically all of the limitations placed on alternating-current motors in order to prevent serious voltage fluctuations may be discontinued in the near future. This is conditional on the use of a device invented by Mr. E. O. Schweitzer, of Chicago, which will automatically and instantly compensate on a lighting circuit for the voltage drop caused by motors connected to the same circuit. A description of this device appeared in the *Electrical Review* of February 6, 1915, together with a diagram of connections and its application to lighting and motor load.

LOAD CONDITIONS AFFECTING THE SELECTION OF MOTORS

Eric A. Lof: In many instances the economy of motor drive is not based so much on the saving in power as on the improved quality and the increased output of the manufactured product. These improvements have been made possible by a careful study of the load conditions of the different machines and by so selecting the motors that their characteristics as well as capacity fully meet the load conditions involved. The use of recording instruments on motors temporarily installed permits the exact size of a motor required for the most efficient operation of any machine or group to be accurately predetermined.

All machines should, of course, be run at their maximum economical speeds, and these speeds should be maintained under all conditions. This is a point often neglected, with the result that the output is in many instances seriously reduced. Certain products are, on the other hand, dependent on a varying speed for their quality, and care must be taken that the right motor is selected for such service.

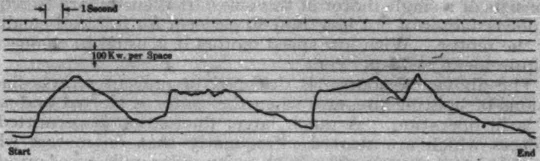

FIG. 4—DUTY CYCLE OF 20-INCH BAR MILL MOTOR

The most ideal load condition would, of course, be that where the load was continuous and constant in value, and with no appreciable speed variation. Such cases are, however, strictly speaking, rarely if ever met in actual practise. The motor may be running continuously for weeks and even months, but the load usually varies more or less. Blowers, pumps, etc., are examples of a continuous and fairly constant load. Certain machines of this class require a high starting torque and if this is not properly considered, the starting current may reach a value which would cause an excessive voltage drop, and this in turn would seriously affect the starting torque, and the motor may not be able to start the load at all.

The load conditions may also be of a variable nature, in which more or less definite cycles are repeated, while the motor is running continuously. Such loads may be irregular in the extreme due to the intermittent character of the process, such as rolling mills, etc.; Fig. 4. For this class of service, flywheels or motors of large flywheel effect are generally used for overcoming the peak loads and thereby reduce the maximum generator and motor capacity required for widely fluctuating loads. In such cases means must be provided for automatically retarding the motor speeds when the peak loads come on, since the available energy taken from the flywheel depends on the drop in speed. This is accomplished by selecting compound-wound direct-current motors, high-slip or phase-wound induction motors, in which latter, resistance may be automatically inserted in the motor winding as the load comes on.

On the other hand, the machinery to be driven may require a frequent starting and reversal with variable speed requirements and sometimes excessive starting torque. Such conditions can readily be met by motor drive, but the operating cycle must be very carefully studied and a motor selected whose characteristics will meet the conditions of the load.

An example of a rather complicated operating cycle is that met with in pipe threading machinery, the accompanying curve, Fig. 5, showing the duty cycle for such an operation. The motor is started at *a*, and accelerated up to a speed of 600 rev. per min., after which the facing operation for the threading begins. This operation terminates at point *c* when the motor is speeded up by means of a field relay to its highest speed of 1200 rev. per min., and the rounding operation begins at point *d* and ends at *e*. Then the field is strengthened and the speed reduced to 400 rev. per min. for the threading, this operation from *f* to *g* requiring the longest time and the lowest speed. At point *g* the motor is stopped by dynamic braking and the operation is repeated when a new pipe has been inserted.

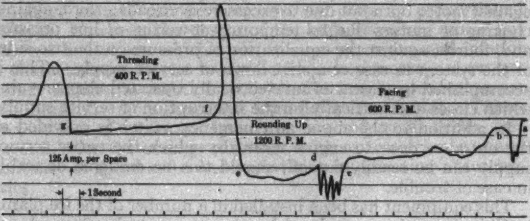

FIG. 5—DUTY CYCLE OF PIPE THREADING MACHINE

It is of course, impossible to cover even a few of all the different conditions of load which are likely to be met in practise, and the above will simply serve to illustrate in a very general way what may be expected and to point out the necessity of carefully analyzing each individual case as certain points always enter which very seldom make two installations alike.

REFRIGERATING MACHINERY

Geo. H. Jones: There are one or two points in electric motor application that I should like to emphasize. The first, in connection with the type of motor selected when variable speed operation is required on direct-current circuits. We find many of the leading architects of the country seem to persist in specifying armature control motors for this class of work. I refer particularly to motor driven ventilating fans and refrigerating machinery. At certain seasons of the year it is desirable to operate these motors at considerably less than full speed, but this results in a very large loss in armature resistance. Field control motors should, of course, be used in this class of work, and a great deal of good can be accomplished if the American Institute will lay emphasis on this point.

For a second item, I would like to call attention to a device developed by the Commonwealth Edison Co., Chicago, for the protection of electrically driven ice plants, against, first, motor burn-out if one phase of service becomes dead; second, against motor burn-out due to excessive overloads; third, against choking of motors due to temporary lowering of line pressure and, fourth, against the equalization of pressure on the two sides of the system in case of a shut down of service supply. This is accomplished by means of an electrically operated clapper valve which closes automatically on the interruption of service supply.

In addition to the above an emergency switch is provided at the entrance door to engine room, by which the entire service supply can be readily cut off, should this be rendered desirable in case of trouble.

This equipment has been installed in a number of the ice plants in Chicago, and is considered by the owners to be very advantageous.

SELECTION OF MOTORS FROM POINT OF VIEW OF FREQUENCY, VOLTAGE AND PHASES AND THE INFLUENCE OF VARIATION AND UNBALANCING OF SAME

N. Currie, Jr.: The average buyer of motors has ordinarily little to say as to the frequency, voltage or phase of his motor applications. The central station supplies his district with lines of certain frequency and phase, and has established rules which govern the voltage to be used on certain sizes of motors, and which allow him to use any one phase of this system only under certain conditions.

To the manufacturer or distributor of power, however, the question may arise as to what would be the voltage, frequency or phase of the power which would offer the cheapest distribution and which would be of greatest convenience and satisfaction to the motor user. This problem would, therefore, be considered by the central station and the isolated plant owner assuming that the use of direct current had been eliminated from the problem.

In any case, this delivered power should be such that standard motors might be used if possible, on account of lower costs and better deliveries and ease in securing supply parts. However, the majority of manufacturers have standardized a wide range of frequencies, voltages, and one- two- and three-phase motors so that usually the choice resolves into a selection from these standard lines.

FREQUENCY

As the speed of an a-c. motor with shunt characteristics (as distinguished from series characteristics) depends on the number of poles of the motor, the range of practical speeds, or more properly, the steps of practical speeds which can be secured, increase with increase in frequency. For instance, the 25-cycle motor is ordinarily furnished in speeds of 500, 750 and 1500 rev. per min., the 40-cycle motor in speeds of 600, 800, 1200 and 2400 rev. per min., the 60-cycle motor in speeds of 600, 720, 900, 1200, 1800 and 3600 rev. per min. Therefore, from this standpoint the higher frequency motor is desirable, although as a rule the above objections to low-frequency motors can be overcome by properly proportioned pulleys. However, the design of the high-frequency motor has inherent limitations which make it more expensive and inferior in characteristics to the moderate-frequency motor. Low-frequency motors, in addition to the limitations in speed steps, are also inherently more expensive from design standpoint. Therefore, motors of moderate frequency, *i.e.*, 50 or 60 cycles, are preferable for the average customer, both as to original cost and flexibility of speed steps and superiority in operating characteristics.

PHASES

Single-Phase vs. Polyphase. As has often been demonstrated, the three-wire general distribution system is superior to the single-phase system, and to the four-wire, two-phase system, both as to cost of copper and cost of installation. However, in certain cases the total cost of installation of a single-phase section may prove cheaper than the three-wire system.

The single-phase motor is in itself inherently larger and more expensive than the polyphase motor. However, where it is necessary to supply power for comparatively small loads, it may be found that the over-all cost of installation of the polyphase motor, with its transformers and three lines of secondary copper, etc., may exceed that of the single-phase motor with its single transformer and two lines of copper. Calculation will easily show the comparative costs for any given case.

Two- vs. Three-Phase. The amount of copper required for a two-phase, three-wire, or for a three-phase system is approximately the same; while the copper required for a four-wire, two-phase, is somewhat greater. Obviously, the installation cost of the four-wire two-phase line would be greater than that of the three-wire system. One of the greatest differences in the cost of installation of two- or three-phase lines would be the cost of the transformers; the three-phase line requiring three transformers, and the two-phase line, two transformers.

The three-phase line, however, offers one big advantage and that is the possibility of using multipolar or multi-speed motors which give adjustable speed characteristics in speed steps depending on the number of poles. This is not possible on two-phase motors. This objection may be overcome, however, by use of various types of adjustable-speed motors which are now appearing on the market and which will give adjustable speed on one- two- or three-phase lines.

The installation of the three-phase motor is slightly more simple than the two-phase motor for the reason that the direction of rotation is the only consideration in connecting up the motor leads, while on the two-phase motors not only must the phases be properly separated, but on three-wire systems there is danger of applying high voltage across the motor windings, with resulting burn-outs. This may seem a minor point but it will be actually found to be the cause of many burn-outs per year.

While performance characteristics on two- and three-phase motors do not differ materially, they are, however, slightly in favor of the three-phase motor as to power factor and efficiency.

VOLTAGE

Transformer ratios make any motor voltage possible. A moderate voltage, *i.e.*, 220 to 550, is preferable as a low voltage means larger secondary copper and a high voltage introduces insulation difficulties both in the distribution lines and in the motor itself. In the high-voltage motor, repairs to windings are more difficult and installation difficulties and troubles due to breakdown are increased.

The high-voltage motor is more expensive, due to increased insulation, and it often has characteristics inferior to the moderate voltage motor, due to sacrifice of active-material space to insulation space. The cost of motor starters or compensators with no-voltage or overload release features is ordinarily higher for the high-voltage equipment.

This whole problem is largely influenced, however, by local conditions and the size of the motor, or motors, involved.

INFLUENCE OF VARIATION AND UNBALANCING OF FREQUENCIES, VOLTAGES AND PHASES

Standard motors are usually guaranteed by the manufacturer to operate satisfactorily on lines which vary a certain percentage in voltage and frequency from the name-plate stamping. The variation covered by this guarantee takes care of the variations ordinarily found in the power delivered to the motor.

There are, however, certain changes in motor characteristics which occur, due to changes in frequency and voltage. If the motor is properly laid out, that is, laid out so that it operates at best efficiency under normal conditions of voltage and frequency, when there is a change from these normal conditions there will be a loss in efficiency, unless there is a corresponding change in the other variable to restore original values.

For instance, a drop in frequency means increased density of field, with lowered efficiency and increased heating. If, however, there is a corresponding drop in voltage, the motor will operate under normal density but with a decrease in output proportioned to the decrease in speed which follows the frequency.

An illustration of this is the satisfactory application of, say, 220-volt, 60-cycle motors to 200-volt, 50-cycle lines with 90 per cent rating.

The ordinary slight unbalancing of voltages across phases has little effect on the operation of the motor. This unbalancing at the most is but a few per cent and although it may result in slightly excess current through one phase of the motor winding, any additional heating would be properly distributed and taken care of by the motor. There would be some loss in efficiency, but this would be slight.

SUMMARY

Motors of standard voltage, frequency and phase should be selected. They should be of moderate voltage and of moderate frequency. Polyphase motors should ordinarily be used, but single-phase motors are preferable in certain cases. Three-phase motors have certain advantages over two-phase.

Due to the liberality in the design of the average American motor, ordinary variations of voltage and frequency do not seriously affect motor operation or characteristics.

ALTERNATING VS. DIRECT CURRENT FROM THE STANDPOINT OF OF THE SUB-CENTRAL STATION, IN CONNECTION WITH SUPPLYING POWER TO MANUFACTURING INDUSTRIES

S. D. Sprong: The first consideration is the demand of the largest single customer to be supplied, as this point decides the class, which may roughly be defined as retail or wholesale; the former being within the scope of what is generally called distribution and the latter falling into the class of transmission. There is another essential difference in this classification besides size of demand, which is, that transmission assumes no lighting (unless especially provided for) and therefore considerable latitude in regulation, whereas distribution is especially for the lighting customer and only permissible for the supply of power to those customers who keep the characteristics of their apparatus and the extent of sudden demand within such limits as not to affect regulation materially.

It is general practise in a-c. distribution to set the limit of capacity of one feeder somewhere between 400 and 800 kw., which limitation automatically defines the line between the largest customer that may be taken on the distribution system and the point where, for larger demands, they must be supplied as transmission customers. There are very evident advantages in carrying the feeder load limit rather high, but there are also numerous disadvantages which, while not so evident, are at the same time of equal or often greater importance. Some of the advantages of large feeder capacity are less unit cost in switchboard and regulating equipment; less pole or duct space occupied; a higher limit as to the maximum single customer that can be supplied, and a somewhat wider diversity factor as between classes of power business and therefore regulation. Among the disadvantages are the wider area of territory covered and, therefore, dependent upon one feeder in case of interruption; the longer runs of primary mains from the center of distribution, which influence regulation because of the impossibility of regulating primary mains individually; therefore, they must be correspondingly large so as to reduce to a very low limit the voltage losses at maximum load. The requirements of regulation are somewhat dependent on the character of territory served, but a strong tendency in the industry as a whole is toward closer regulation, due partly to the character of services and devices supplied from the system, and the growth of the section both in extent and character.

Generally speaking, it is desirable to limit the size of the maximum of a single customer on a feeder to 50 per cent of the feeder load. While this is an arbitrary figure and therefore there must be exceptions, it is a convenient one in practise principally because customers of the larger capacities sometimes require reserve service from another feeder; consequently if the individual demand much exceeds half the feeder capacity and it is found necessary to throw it on a reserve feeder which is already carrying probably three-quarter load, it would be incapable of carrying a larger percentage of extra demand than that given. One of the exceptions to this rule, applied where it is impracticable to give direct transmission service, is to run a number of duplicate feeders of standard size to the particular customer. Standard equipment is used, at the same time insuring continuity of service to nearly full capacity because of the multiple feeders.

Considering briefly some of the principal systems of primary a-c. distribution that are in general use, there are the three-wire two-phase, the four-wire two-phase, the three-wire three-phase and the four-wire three-phase. With the exception of the three-wire three-phase, which has special difficulties in independent phase regulation and is nearly obsolete, the other three systems have demonstrated their practicability and are in wide general use.

Where conditions, due either to radical changes to be made in the method of distribution or the development of new districts, permit of free choice of systems, it would seem that for a given potential between lines, the four-wire two-phase should give all-around satisfaction. It has the advantage of simplicity, complete independence of its phases and therefore no difficulty in independent phase regulation, greater facility for keeping phase balance as there are but two phases to be considered, and, particularly in large lighting installations, the load needs to be divided into but two parts. The three-wire two-phase system is essentially a single-phase system so far as the lighting load is concerned. In the case of the four-wire three-phase there is the problem of maintaining approximate division of load between the three phases, which in large lighting installations is more difficult, and the further objection that the integrity of three otherwise independent single phases is dependent on one (the center) conductor.

In a few systems, it is general practise to install independent lighting and power transformers; this custom having probably developed from the difficulty of controlling either the size, due to the limitations of what the manufacturers offered, or characteristics of the motors, especially for elevators. While this arrangement has certain advantages, such as permitting a wider latitude in the requirements in motor specifications and other power consuming devices, it is on the whole questionable whether it is justified. It is, speaking relatively, just as important to have a high load factor on the distributing transformers as on any other part of the system. With combined light and power loads the average transformer load factor probably is not better than 12 per cent to 15 per cent, therefore, it will be seen how important it is that nothing be done to reduce this figure still further, which will be the result where lighting and power loads are carried on independent transformers. It seems much better general practise to keep both kinds of load on the same secondary system, making the latter a heavy network where practicable and so limiting the size and character of motor installations as not to interfere seriously with regulation. In most systems there is a large field for improvement along the line just referred to, that of increasing the load factor on transformers and at the same time the general service conditions of regulation, continuity, etc., by the substitution of fewer and larger transformers interconnected by heavy network and protected in turn against general shut-down due to transformer failures by suitable devices.

Considering the problems of supply of power from the transmission system, these are generally of a more or less special character and therefore no particular set of conditions can be taken as typical. One consideration usually applies to all, and that is, not to lead the customer to expect, nor permit him so to design his own installation as to require, retail regulation from a wholesale service. This class of customer does not always appreciate that there is such a distinction between a large and small service, and its lack of consideration at the time the contract is negotiated may some time later bring up troublesome problems of voltage or speed regulation.

On the problem of supplying power from a d-c. system, there is not so much to be said nor so many debatable questions to be considered. It may be assumed that where a new territory is expected to develop a relatively scattered industrial load a d-c. system would not be selected, also that where certain districts in an already built-up territory develop heavy industrial demands, a second system especially for miscellaneous power distribution would not be installed. For it is safe to say that any district which orginally justified an underground d-c. system would have been of such a promising character financially that the unexpected development of unusual industrial demands could readily be met by additions to the existing equipment. Experience in the d-c. areas of the larger cities has fully demonstrated that any demands within their territory can be properly met from the direct-current system, with the occasional exception of special processes or the unusual demands that far exceed the practical limits of either the d-c. or a-c. distribution systems, and which naturally fall into the class of transmission customers.

From an engineering point of view, there is practically no limit to the amount of power that can be commercially taken care of by the d-c. system; but as a practical matter, the questions of unusual demand generally answer themselves by the installation of a local substation on the property where the requirements exceed 1000 to 2000 kw. A customer requiring such large power supply for industrial purposes is at the same time provided with an engineering force that can properly care for and operate the necessary substation equipment, thus avoiding the congestion of subways in the vicinity of the property which would result from taking so much power at the usual three-wire distribution voltage.

To sum up, it appears that a broad analysis of the particular problem to be met will evolve its own general answer, but still with sufficient latitude as to require the application of sound judgment and the knowledge gathered from actual experience.

THE FACTORS INVOLVED IN MOTOR APPLICATION, FROM THE STANDPOINT OF CENTRAL STATION COMPANIES

R. M. Wilson: The chief factors in which the central station companies are directly interested, in supplying service to motors, are as follows:

Starting current and starting conditions,
Power factor of the load,
Fluctuations of load,
Size of units,
Starting devices,
Type and voltage of motor, and
Hours of service.

It is necessary to limit the starting current taken by motors as a protection to the station equipment and to the service of other customers supplied from the same circuit. Where the starting current is excessive it follows that service of other customers on the line will be seriously affected, which, besides causing a good deal of trouble, in the way of fuses blowing out, strain on transformer, etc., necessarily means that continual complaints will be received from customers, due to annoyance and interference with their business owing to frequent stopping of their motors caused by heavy drop on the line. Conditions of this kind would naturally be a bad advertisement for a central station company and very often might lead to the losing of a considerable amount of good business by customers so affected. The demand on central station oil circuit breakers and other equipment is of course seriously affected in the case of troubles due to heavy starting current of more or less large power users.

Coupled with the starting current can also be included the class of service, that is to say, whether the load is a fluctuating one or a fairly steady one. Motors which are starting and stopping frequently and motors having a fluctuating load are undesirable from the point of view that excessive amounts of investment in lines and transformer capacity are required to minimize conditions of this kind, and to protect, as far as possible, the service of other customers supplied from the same mains. The above conditions are more pronounced, and therefore more serious, the larger the units.

The question of power factor is of importance in connection with the drop and line losses and relatively higher capital expenditure if the power factor is low.

Where a system comprises a large percentage of power business with low power factor, due to unrestricted conditions of the customers' equipment in this respect, it even becomes necessary to install synchronous converters to raise the power factor of the system as a whole.

Motors of the squirrel cage type give a lot of trouble to central station companies, due to the relatively high starting current taken, particularly if the units be large. Wire-wound rotors are very much more preferable in motors of more or less large capacity, from the central station point of view.

The size of units is of importance, inasmuch as the question of capital investment to supply service to them is of course involved. Where motors exceed a certain size, depending on their location relative to the nearest substation, it becomes necessary to provide special circuits for the sole supply of such service. The size of the units prohibits the load being taken on the nearest available feeders. The benefit of diversity factor of load which is obtained where feeders supply a number of customers with relatively small size motors is less in such cases. The capital investment then has to be all charged against that particular service which it supplies. The question of voltage of the supply feeder has to be considered in these cases, and the economical point of the line investment is the governing feature as to whether such service is to be supplied at the usual distribution voltage of 2200, or higher voltages, usually not exceeding 13,000 volts. There are exceptions, of course, in the case of very large blocks of power which are sometimes tapped directly off high-tension transmission lines when available. It is inadvisable on general principles to go beyond the 2200-volt limit in city distribution, unless the expense of this voltage would be absolutely prohibitive. In outlying territory and suburban districts where the amount of load to be provided for involves special provision, it is usually more economical to supply at 13,000 volts.

The question of the voltage of motors, themselves, is largely governed by the size of the units. On some systems the standard voltage for polyphase motors is 550 volts. For units of 100 h.p. and over it is found more economical to endeavor to have the motors wound for 2200 volts. Where the number and size of transformers required for a motor load are such that their installation on poles is difficult, a fireproof transformer house with oil circuit breakers and disconnecting switches mounted on marble panels becomes necessary. This is an item of expense which has to be considered in contract price for the supply of power.

Another feature in the question of rates for power in more or less large blocks, particularly where the service is of considerable importance, is that of having a standby service available so that two sources of supply are provided from two separate circuits. Where the load warrants this and where the expense is not prohibitive it is a good policy to adopt such service, inasmuch as the continuity of service to a large installation of this nature is not only imperative to the customers and to the fulfilment of the contract, but is probably the best advertisement that a central station company could have. Where service is supplied from high-tension lines, that is to say from 5000 volts upwards, a double service of this nature is practically imperative, inasmuch as the necessity for line repairs and other work to be carried out necessitates the shutting down of a line. This is difficult of accomplishment without two services, as it is entirely likely that it cannot be arranged to interrupt the service of large power customers for sufficient length of time to carry out the work.

In supply of large blocks of power it is usual to endeavor to supply some on a limited service basis. That is to say that the whole or a certain percentage of the load will be off during peak load period, say from 4.30 to 6 p.m. during the period from Nov. 15th to March 1st. The advantages of special circuits to installations served on limited service basis on more or less large blocks of power are obvious, as a check on the fulfilment of contract conditions in this respect.

Considerable trouble has been experienced with motors operating a certain class of service, for example, motors operating refrigerating machines, air compressors, pumping with automatic starting devices, etc.

In two instances where motors were driving refrigerating machines, a serious disturbance occurred on the system from pulsating, causing the lights to flicker. It was found that this flickering took place more particularly on a certain step of the controller. Ultimately it was necessary to provide additional special resistances to overcome the difficulty. The apparent cause of the rapid fluctuation noticeable on the lights supplied from the same feeder circuit was difficult to determine, but seemingly was due to something peculiar to this type of apparatus. The effect was as if the motor tended to reverse at certain periods of the stroke of the compressor or refrigerator machine.

Difficulties experienced with motors driving automatic pumps are frequently met with, particularly where the motors are of fairly large size, and, of course, the resultant effect on the distribution system is intensified the longer the feeder circuit. Even by greatly increasing the capacity of the line at considerable expense it is often found difficult, in fact practically impossible, to overcome disturbing effects caused by service of this kind.

Where a large amount of power service is supplied from an extensive overhead system, which is perhaps feeding from several generating stations, and particularly where distribution circuits are subject to transfer from one source of supply to another in the course of load despatching, it is most advisable to endeavor to have customers' motors equipped with no-voltage and overload releases. Otherwise the blowing of fuses, and sometimes the burning out of the customers' motors, is a frequent occurrence.

It is most advisable to insist on having starting compensators on all motors of 5 h.p. and larger.

It is not advisable to have single-phase motors connected to the lighting circuits in larger sizes than 5 h.p. It is not advisable on account of the capital expenditure involved in the furnishing of transformers, etc., to contract for supplying polyphase motors less than 5 h.p.

It is difficult to insist on and obtain all the conditions that one would like from the central station point of view when contracting for supply of power to customer. This is particularly the case where there is competition for such service, yet it is essential for successful operation that central station companies should insist on certain conditions being observed. It is advisable where competition is to be met that for their own protection, central station companies supplying service in the same locality arrive at an understanding of these conditions between themselves, and insist on them when securing power business.

It is advisable that the special conditions, features and regulations which central station companies desire be embodied in the contract made with the power user and be specifically covered by clauses of such contract.

Clauses in contracts for power should cover power factor which the company desires; the starting current of the motors; the conditions of operation, as affecting the company's system, both as to the frequent starting and stopping of motors and fluctuation of load; the voltage of motors, depending on the size; the type of motor, whether squirrel cage or wire-wound, depending on size; the provision for transformer house to be built by the customer where such is needed, and the protective devices, starting devices, relays, etc., which may be deemed advisable.

The power factor of individual motors or the power factor of the aggregate load should never fall below 80 per cent and on larger units should be higher in proportion, commonly reaching 92 per cent.

Where the power factor falls below that specified in the contract, power should be charged for pro rata on a power factor basis.

The starting current of the motor should be limited to 2½ times full load current of the motor. Motors of 100 h.p. and over should be of the wound-rotor type and should operate at 2200 volts.

Services from which disturbance on the system may be expected, such as automatic pumps, air compressors, refrigerators, rolling mills, cranes, etc., should be covered by special clauses, so as to limit the disturbance, and to call for special devices or method of operation to insure this end. It is preferable to lose the business rather than to contract for a service that will introduce a disturbance on the system, which will make the service to other customers unsatisfactory and from which continued complaints might be expected.

Presented at the joint meeting of the Chicago Section of the American Institute of Electrical Engineers and the Western Society of Engineers, Chicago, Ill., March 22, 1915.

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THE FLOW OF ENERGY

BY ROBERT A. PHILIP

Abstract of Paper

A new graphical method of representing the flow of energy is described and pictures are drawn showing the functions of generators, motors, transformers, transmission lines and other parts of an electric distributing system in terms of the flow of energy through them.

The method is based on using two ribbons; one to represent the flow of energy proper, and the other (not used for direct currents) representing the magnetizing power. It is shown that various phenomena of alternating-current transmission are determined by the widths and directions of the two ribbons.

The principal elements of the picture (generators, synchronous motors, induction motors, etc.) are taken up one by one and in simple combinations, each case being illustrated by typical figures.

THE flow of a material fluid, such as water or air, through the pipes which transmit it may be shown as a ribbon whose varying width represents the variations of the current.

A similar picture may be drawn of the transmission of power.

It is, however, more exact to consider that it is energy rather than power which is being transmitted because power means a flow of energy. The relation between power and energy is similar to that between a current of water and the water itself. That is, power is a name for a current of energy.

Energy, like matter, can be transported or changed in form but can be neither created nor destroyed. Therefore in the distribution of energy, as in the distribution of a material fluid, the total quantity supplied to the distributing system, plus or minus storage in the system itself, must at every instant equal the quantity delivered, including leakage. This fundamental similarity allows a distribution of energy to be pictured as though it were a distribution of matter.

Fig. 1 is a picture, on this basis, of the flow of energy into, through and out of a rotating shaft. Along the route of the shaft a ribbon is drawn, the width of the ribbon at each point being proportional to the flow of energy, that is, the power, at that point. Evidently, if there is no storage in the shaft the width of the ribbon can only increase at points where energy flows in and only decrease where it flows out, and a change in width of the ribbon representing the main stream of energy must be exactly equal to the width of a branch at that point. The flow of energy may be measured in any convenient unit, horse power, foot-pounds per second or kilowatts, and the width of the ribbon may be drawn to any desired scale. At each point the flow has two elements, amount and direction, the former being represented by the width of the ribbon and the latter indicated by arrows marked on the ribbon.

This first illustration is based on the transmission of energy through a rotating shaft where the energy comes in and goes out over moving belts and is lost in bearing friction. A similar illustration may be used for the hydraulic and pneumatic transmission of energy by currents of water and of air and for the electric transmission by electric current.

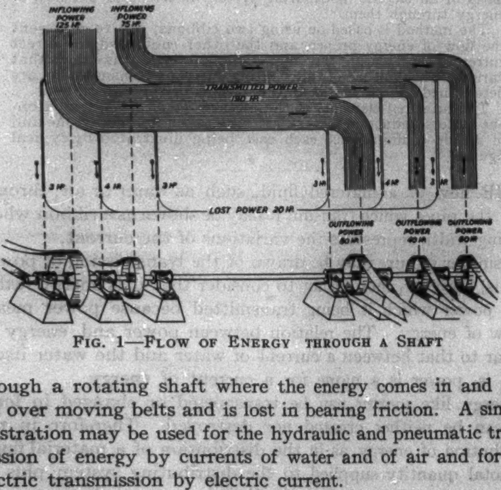
INFLOWING POWER 125 HP
INFLOWING POWER 75 HP
TRANSMITTED POWER 190 HP
3 HP
4 HP
3 HP
3 HP
4 HP
3 HP
LOST POWER 20 HP
OUTFLOWING POWER 80 HP
OUTFLOWING POWER 40 HP
OUTFLOWING POWER 80 HP

FIG. 1—FLOW OF ENERGY THROUGH A SHAFT

The picture drawn is a general one and may be used to represent the transmission of any kind of energy in any manner.

Energy may be transmitted in one form, transformed and transmitted further in another form and the several transmissions may be grouped together to form a single picture.

Fig. 2 shows energy transmitted thermally from a steam boiler through a steam pipe to an engine, thence mechanically through a belt to a dynamo and finally electrically to a motor.

The diminution of the stream of energy is indicated as due to separate thermal and mechanical losses of transformation in the engine, mechanical losses in the belt, combined mechanical and electrical losses of transformation in the dynamo and electrical losses in the wires.

The picture may be extended by tracing each branch forward or back to its furthest ascertainable end and it may be amplified by analyzing the losses into more elementary streams and by tracing the flow in greater detail; showing, say, the flow of energy through the reciprocating parts of the engine on its way from the steam pipe to the belt.

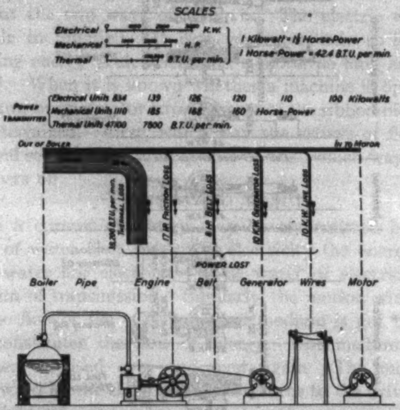
SCALES
Electrical K.W.
Mechanical H.P.
Thermal B.T.U. per min.
1 Kilowatt = 1⅓ Horse-Power
1 Horse-Power = 42.4 B.T.U. per min.
Power Transmitted
Electrical Units 834 139 126 120 110 100 Kilowatts
Mechanical Units 1110 185 168 160 Horse-Power
Thermal Units 47100 7800 B.T.U. per min.
Out of Boiler
In to Motor
39,700 B.T.U. per min. Thermal Loss
17 H.P. Friction Loss
8 H.P. Belt Loss
10 K.W. Generator Loss
10 K.W. Line Loss
POWER LOST
Boiler
Pipe
Engine
Belt
Generator
Wires
Motor

FIG. 2—THERMAL, MECHANICAL AND ELECTRICAL TRANSMISSION

While this is a general method of picturing the transmission of power, it is especially useful in illustrating the meaning of terms used in electrical power transmission by alternating currents, such as wattless current, synchronous condenser and induction generator, therefore the electrical use of the method will be chosen for amplification, although it will be indicated that the same things may be found in mechanical transmission.

THE DIRECT-CURRENT GENERATOR AND MOTOR

In Fig. 3 the varying widths and directions of the ribbon of energy flow show the operating characteristics of generators and motors. The width of the outgoing energy stream is of course exactly proportional to the load, but is electrical power from a generator and mechanical power from a motor. The width of the loss stream is a maximum at full load and decreases slightly down to a minimum at no load. The input stream is exactly equal to the output stream plus the loss stream; that is, the losses are necessarily drawn from the inflow, so are supplied mechanically for a generator and electrically for a motor. The main current of energy tapers down as it passes through the machine.

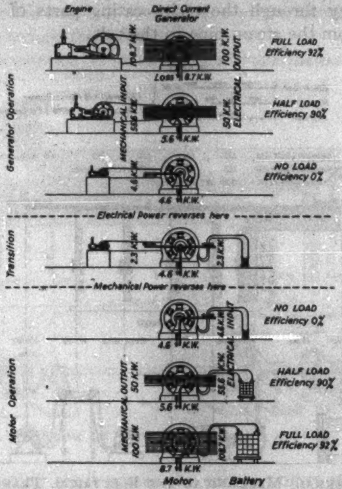
Engine
Direct Current Generator
108.7 K.W.
100 K.W. OUTPUT
FULL LOAD Efficiency 92%
Loss 8.7 K.W.
MECHANICAL INPUT
55.6 K.W.
50 K.W. ELECTRICAL
HALF LOAD Efficiency 90%
5.6 K.W.
Generator Operation
4.6 K.W.
NO LOAD Efficiency 0%
4.6 K.W.
Electrical Power reverses here
Transition
2.3 K.W.
2.3 K.W.
4.6 K.W.
Mechanical Power reverses here
4.6 K.W. INPUT
NO LOAD Efficiency 0%
4.6 K.W.
MECHANICAL OUTPUT 50 K.W.
55.6 K.W. ELECTRICAL
HALF LOAD Efficiency 90%
5.6 K.W.
Motor Operation
100 K.W.
108.7 K.W.
FULL LOAD Efficiency 92%
8.7 K.W.
Motor
Battery

FIG. 3—DIRECT-CURRENT GENERATOR AND MOTOR OPERATION AT VARYING LOADS

The efficiency is equal to the outflow divided by the inflow. The illustration shows clearly one important point: the efficiency increases from no load to full load not because of a decrease in losses but in spite of an increase in losses.

The series of pictures may be considered as a moving picture film of the operation of a direct-current generator. It is first running in multiple with other sources of electric power and carrying full load. The operator turns the rheostat handle increasing the resistance of the field circuit and the outflow drops perhaps to half load; he turns the handle further and the outflow drops to zero, the reduced load on the engine being indicated by showing the engine as proportionally smaller. If the operator continues to turn in resistance the flow of electric power reverses. There is here a narrow transition stage where the losses, which are now at a minimum, are supplied both mechanically and electrically. When further resistance is turned in, the mechanical power also reverses and operation as a motor follows at no-load, fractional load, full load and overload in successive steps.

The series illustrates the meaning of the terms generator and motor. They describe not the construction of an electric machine but the two ways of using it. The electric machine is reversible in function. It is a generator only so long as the outflowing energy is electrical and a motor so long as it is mechanical. When it is known whether a machine is operating as a generator or as a motor two elements of the ribbon picture have been determined. First, which way the arrows of flow should point, and second, as a consequence of this, which way the main flow tapers off.

TRANSMITTING MEDIUM

While a current of energy may be transmitted by using a current of water or a current of electricity the energy itself is neither water nor electricity. The water or electricity is but a medium of transmission. Similarly, the motion which constitutes the flow of the water or other medium is not the motion which constitutes the flow of energy. The medium may be, and often is, used over and over again. The moving belt goes forward on the slack side and returns to the driving pulley on the tight side; the water goes out in the pressure pipe, leaves the engine through the exhaust pipe and may return to the pump through the suction pipe; the electricity goes out on the positive wire and returns to the generator on the negative wire. Just as much belt, water or electricity comes back as goes out, but the transmitted energy moves forward only. In fact the direction in which the belt, water or electricity moves can be reversed without reversing the direction in which energy is transmitted, or vice versa.

Therefore, if energy is transmitted by a flow of water or of electricity a picture of the flow of energy will not be at all identical with a picture of the flow of the transmitting medium, even though the same principles may be used in representing each kind of flow.

It will be understood that a representation of a flow of electrical energy is not at all a representation of a flow of electricity.

That the motion of energy and the motion of the transmitting medium are practically independent is also shown by the fact that shafts, belts, water and electricity may be in active motion and yet transmit no power, and that the same mediums may transmit more power at times when they move slowly than when they move rapidly.

This is because the mediums transmit no power unless they move under pressure or tension. Power, whether mechanical or electrical, is considered as consisting of two equally important components, one of motion and one of pressure. The amount of power is the product of the two components. For hydraulic transmission the power in foot-pounds per second is the product of the flow in cubic feet of water per second by the pressure in pounds per square foot, and similarly, for electric transmission, the power in watts is the product of the current of electricity in amperes by the electrical pressure (potential) in volts.

ALTERNATING CURRENTS

Where power is transmitted mechanically by shafts, belts or fluids, or electrically by direct currents, the motion and pressure each has its own fixed direction. However, power is also transmitted both mechanically and electrically by motions and pressures which alternate in direction periodically. The pistons, piston rods, connecting rods and other reciprocating parts of a steam engine transmit mechanical power by virtue of their motion although this motion alternates in direction instead of being uniformly forward. In these cases it is important to note that the pressure as well as the motion also alternates. The pressure is on one side of the piston on the forward stroke and on the other side on the backward stroke.

Energy is the product of motion and pressure, therefore, if motion and pressure both reverse, the flow of energy is not reversed, on the principle that the product of two negatives makes a positive. The reversal of the motion of the reciprocating parts of a steam engine does not reverse the motion of the energy which flows forward from steam pipe to shaft during the backward as well as forward stroke.

With uniform motion or flow the amount of energy transmitted is equal to the product of the motion by the pressure. The same formula holds for reciprocating motion and alternating flow, provided it is understood that by motion and pressure are meant mean motion and mean pressure. The mean is found by squaring the instantaneous values of the quantities, averaging these squares over a complete cycle and extracting the square root.

The transmission of power by electric current which alternates in its direction follows the same principle as the transmission by reciprocating mechanical motion, namely, the reversal of the direction of the electric current does not reverse the flow of energy, because the pressure is simultaneously reversed. An alternating current of electricity, or of water for that matter, will transmit just the same amount of power as a direct current of the same mean magnitude, at the same mean pressure, provided, however, that the current and potential reverse at exactly the same time.

When the motion and pressure reverse simultaneously they are said to be in phase. Alternating motions or currents when in phase with their corresponding alternating pressures are practically equivalent to uniform motions or direct currents for the transmission of power.

Under these conditions the ribbon picture of power may be used for alternating-current transmission. However, it is to be remembered that the flow represented is not the instantaneous flow, which fluctuates, but the mean flow over one or more complete cycles.

ACCELERATING POWER

It may happen that while the motion and pressure are both reciprocating or alternating, and at the same rate, they fail to reverse simultaneously.

The difference in time of reversal may be very small, but it cannot be greater than a quarter of a cycle. When motion and pressure reverse a quarter of a cycle apart, any further change in either direction brings the times of reversal closer together. For example, two cranks on the same shaft have their respective dead points as far apart as possible when set, like the cranks of a locomotive, a quarter of a revolution apart. Motion and pressure are then said to be in quadrature and each reverses when the other is at a maximum.

Under these conditions motion and pressure, instead of being positive and negative simultaneously, thereby always giving a positive product, are of the same sign but half the time, so that their product is half the time positive and half negative.

This change in sign of the product, that is, of the power, indicates a reversal of its direction of flow. Where motion and pressure are in quadrature the energy flows forward and backward instead of moving uniformly forward. The average of the forward and backward flow is zero, so that such an alternating flow of energy does not constitute a transmission of power in the ordinary sense.

The phenomenon of motion and pressure in quadrature occurs wherever a mass moves with a reciprocating motion. The motion is that of the mass, and the pressure that required to accelerate it. The power corresponding to their joint effect may be called accelerating power.

The power transmitted by reciprocating motion is equal to the product of the mean velocity and mean pressure when motion and pressure are in phase. The rule may be extended to apply to accelerating power.

The product of the mean velocity by the mean pressure, where motion and pressure are in quadrature, is an amount of power equal to the maximum value which the accelerating power attains during a cycle. The momentary flow at all times is proportional to this maximum. As the flow alternates in direction, giving an average value over the cycle of zero, it is convenient to use the maximum value as a measure of the flow where considering it in connection with the associated flow of energy over one or more complete cycles.

For reciprocating motion, the product of mean velocity by mean pressure is the transmitted power if the two quantities are in phase, but is the accelerating power if they are in quadrature.

Accelerating power is evidently always necessary where reciprocating motion is maintained. On the whole the accelerating power neither adds to, nor substracts from, the true power transmitted. It may exist where there is no true power transmitted, and for a given amount of true power the accelerating power may be greater or less. Finally it may be said that accelerating power is a peculiar form of power fundamental to reciprocating motion and that it may be considered as transmitted independently of the true power and according to its own laws.

The steam engine, containing reciprocating parts, furnishes an example of the transmission of accelerating power.

Consider a steam engine with steam shut off and running due to the momentum of the flywheel. Aside from any effects of friction or of compression in the cylinder, the reciprocating parts, the piston for example, must be accelerated from rest to a maximum velocity, then retarded (accelerated negatively) and brought to rest again in each stroke. These accelerations require forces which must be transmitted to the piston from the flywheel through the intervening parts, such as the piston rod, as pressures (or tensions, which are negative pressures). The reciprocating parts are therefore transmitting accelerating pressures and at the same time are in active motion. However, it will be found that the motion of the rod reverses at the time when the pressure in it is a maximum and that the pressure reverses when the velocity is a maximum. That is, motion and pressure are in quadrature.

The flywheel is giving out power and accelerating the piston during half the time and during the other half the process is reversed. It may be said that the flywheel and the piston are interchanging accelerating power which alternates in direction.

At the instant that the reciprocating parts are passing their dead point the flywheel has a maximum velocity which is the same as though it were running freely unconnected to the reciprocating parts. At all other times the velocity of the flywheel is more or less reduced. Consequently, if reciprocating parts are connected to a flywheel previously running freely the number of revolutions per minute will thereby be reduced.

The flywheel contains a store of energy by virtue of its velocity. This reduction in the mean velocity results in a corresponding reduction in the average energy stored in the flywheel, but on the other hand the reciprocating parts acquire an equal amount of average energy due to their mean velocity.

From this point of view it may be said that the reciprocating parts have been energized at the expense of the flywheel, which has been deenergized. The total stored energy of the system has not been changed but it has been redistributed.

In a steam engine, whether a simple engine with a single cylinder and crank, or a compound engine with several cranks, the motion of all the reciprocating parts, pistons, piston rods, connecting rods, valves, valve rods, and eccentric rods, is in proportion to a single angular velocity, the speed of revolution of the engine. The distribution of accelerating power in one engine may form a complex system, all, however, based on a single angular velocity. In this respect it is similar to an alternating-current distributing system, which, however large, has a single frequency.

Where the mean angular velocity is constant the energizing of the reciprocating parts and the de-energizing of the rotating parts is directly proportional to the amount of accelerating power which flows. For example, if the weight of a reciprocating part is doubled, the energy it contains and the accelerating power it receives are both doubled, while if the stroke is doubled the energy and accelerating power are each quadrupled. At constant angular velocity, the amount of accelerating power may be used as a measure of the transfer of energy, and it may be said that each reciprocating part takes a flow of accelerating power proportional to the amount to which it is energized, while each rotating part is de-energized in proportion to the flow of accelerating power which it gives out.

PICTURES OF ACCELERATING POWER

To make a picture of the flow of accelerating power a second ribbon may be drawn of width equal to the accelerating power, that is, to the product of the mean force by the mean velocity. To distinguish between the two ribbons, that for energy transmission will be shaded longitudinally and that for accelerating power laterally.

Accelerating power may be measured in the same units as other power, that is, foot-pounds per second, horse power, watts or kilowatts.

Arrows have been placed on the energy flow ribbon to indicate that energy is continually passing a given point in one direction. With such a flow the total quantity of energy passed increases cumulatively with the time. The flow of accelerating power alternates in direction so that arrows to represent the successive instantaneous flows would point equally in both directions. However, in picturing the transmission of power by reciprocating motion we are not attempting to show the instantaneous values which fluctuate throughout the cycle but only the effect over one or more complete cycles.

While the accelerating power has no direction of flow it is associated with the transfer of energy from the rotating flywheel to the reciprocating piston, which is in a determinate direction. As the de-energizing of the flywheel and the energizing of the piston are each proportional in magnitude to the width of the stream of accelerating power, it is a useful convention to mark on this ribbon arrows to indicate the direction of the transfer of energy. It is to be remembered that this transfer is a process not cumulative with time, so that accelerating power of a constant amount may flow indefinitely from a flywheel without depleting its energy supply. The arrow on this ribbon represents a transfer of energy which occurs at the time when the flow from flywheel to piston first begins and which may be described as unstable. The transfer can only be maintained as long as the flow of accelerating power continues and in an amount proportional to the flow. Any increase or decrease of flow is accompanied by a corresponding transfer of energy.

It is further to be remembered that the direction of these arrows is determined by making the assumption that the rotating parts are the primary reservoirs of stored energy; therefore, that the flow of accelerating power (transfer of stored energy) is from the rotating parts to the reciprocating parts. This assumption is natural in the simple case used for illustration, but is not essential. That is, the direction of the arrows results from a convention and could be reversed by adopting a different convention. It is of course desirable to adhere always to one convention, though it is useful to know that the arrows on the ribbon of accelerating power represent but one of two possible views. The conclusions are of course the same whichever view is adopted, the language in which they are clothed being alone affected.

Fig. 4 shows the distribution of accelerating power from a flywheel to the reciprocating parts of an engine.

The speed of the engine is 150 rev. per min. The stroke of the engine is two feet, giving the pistons a mean velocity of $\pi/\sqrt{2} \times 150$ rev. per min. $\times$ 2 feet, or 667 feet per minute. The mean acceleration of the pistons is $\sqrt{2} \times \pi^2 \times 150^2$ rev. per min. $\div 60^2$ seconds per minute $\times$ 2 feet, or 175 feet per second per second. The high-pressure piston weighs 120 pounds and takes a mean accelerating force of 120 pounds × 175 feet per second per second divided by 32.2, or 652 pounds. The accelerating power is therefore 652 pounds × 667 feet per minute divided by 33,000, or 13 horse power.

The low-pressure piston weighs four times as much and requires 52 horse power acceleration. The valve weighs one-sixth as much and has one-fourth the travel and requires 1/96 the power, or 0.14 horse power.

The high-pressure piston is energized to an amount equal to one-half its weight multiplied by the square of its mean velocity or $1/2 \times 120$ pounds $\times 667^2$ feet per minute divided by 60^2

seconds divided by 32.2 = 230 foot-pounds. The low-pressure piston contains 920 foot-pounds energy and the valve 2.4 foot-pounds. These quantities of energy are exactly proportional to the accelerating power taken by the parts, the ratio being 33,000 foot-pounds per minute divided by 4 × π × 150 rev. per min. or 17.5. That is, a reciprocating part is energized by 17.5 foot-pounds for every horse power of accelerating power which flows into it.

MAGNETIZING POWER

What has been said of mechanical motion and pressure when in quadrature applies also to electric currents and pressures.

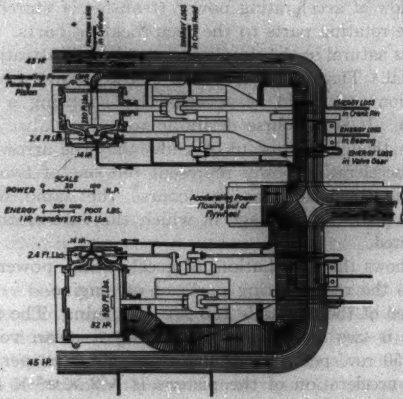
Friction Loss in Cylinder
Energy Loss in Cross Head
45 H.P.
Accelerating Power flowing into Piston
13 H.P.
230 Ft. Lbs.
2.4 Ft. Lbs.
.14 H.P.
Energy Loss in Crank Pin
Energy Loss in Bearing
Energy Loss in Valve Gear
SCALE
POWER 0 50 100 H.P.
ENERGY 0 500 1000 FOOT LBS.
1 H.P. transfers 17.5 Ft. Lbs.
Accelerating Power flowing out of Flywheel
.14 H.P.
2.4 Ft. Lbs.
920 Ft. Lbs.
52 H.P.
45 H.P.

FIG. 4—FLOW OF ENERGY AND ACCELERATING POWER THROUGH ENGINE

As reciprocating motion necessitates acceleration of matter and that requires the application of accelerating power, so alternating electric currents necessitate the acceleration of electricity and that also requires a similar kind of power. Mechanically, the accelerating power is stored intermittently as kinetic energy in the reciprocating mass, while electrically, the power is correspondingly stored in the alternating magnetic field of the moving electricity. Wherever there is reciprocating matter there must be mechanical accelerating power and wherever there is alternating electricity there must be electric magnetizing power.

Electric currents in quadrature with the electrical pressure have been called idle or wattless currents because they transmit no power in the ordinary sense, and the product of these currents by the pressure has been called wattless power for the same reason. As the power taken by reactive coils is almost wholly "wattless" the power is also called reactive power, with the advantage that there is no implication that it is not really power. As the "idle" currents produce magnetization they are also called magnetizing currents, and the name magnetizing power seems to give the simplest view of the function of reactive power. All of these electrical terms describe a special form of power which alternates in direction and is otherwise identical with mechanical accelerating power which exists in all reciprocating machines.

Magnetizing power, it should be noted, is necessary to produce magnetism alternating in direction, just as accelerating power is necessary to produce reciprocating motion.

When the magnetism is uniform in direction the magnetization is produced once for all at the beginning and no further magnetizing power is required. The same distinction occurs in mechanics: uniform motion, say of a flywheel, requires accelerating power only at the time of starting; after reaching speed it will run indefinitely without further acceleration.

A permanent magnet or an electromagnet excited by direct currents may be regarded as a reservoir of magnetism just as a uniformly moving flywheel is a reservoir of energy.

The magnets used in direct-current electrical machinery are of this type, therefore, except at the instant of starting, no magnetizing power is used.

A permanent magnet may be compared to a frictionless flywheel which will run indefinitely when once started. Flywheels in general cannot be frictionless but must have shaft and bearings. To keep such a flywheel running uniformly, energy must be continually supplied equal to the bearing friction. But it should be noted that *such energy adds in no way to the stored energy of the flywheel.* A direct-current electromagnet is similar to such a flywheel. The field current or exciting current merely overcomes electrical friction, that is, resistance, and conserves the magnetization put in at the first instant.

The magnetizing power flowing into an alternating-current magnet is like the accelerating power flowing into a reciprocating piston ,while the exciting power flowing into a direct-current magnet is like the mechanical power flowing into the bearings and overcoming the friction of a flywheel.

In practically all commercial machines for interchanging mechanical and electrical power, that is, generators and motors, the mechanical forces are due to the attraction and repulsion of magnets. With alternating-current machines the magnetism of these magnets is produced in whole or in part by this magnetizing power.

An ordinary alternating-current generator also has magnets excited by direct current. These magnets serve a similar purpose to the flywheel of a reciprocating engine. As the flywheel is a reservoir of mechanical energy which is drawn on to accelerate and retard the reciprocating parts, so the magnet of the alternator is a reservoir of magnetization which magnetizes and demagnetizes the alternating-current magnets of the circuit.

As we may picture mechanical accelerating power flowing out from the flywheel to each reciprocating part, of an engine, so may we picture magnetizing power flowing out from the generator to each motor, transformer or other part containing an alternating-current magnet.

The alternating-current magnets are magnetized at the expense of the direct-current magnets. The gain of magnetization of one exactly equals the loss of magnetization of the other.

A displacement of magnetization in a determinate direction is then associated with the flow of magnetization, which being alternating, is itself directionless. Furthermore, the frequency being the same throughout the system, the amount of magnetization displaced is proportional to the magnetizing power.

Electric machines absorb or give out mechanical energy because of attraction or repulsion of their constituent magnets. Alternating-current machines such as ordinary generators, synchronous motors and synchronous converters contain both direct- and alternating-current magnets, while other important electric machines such as transformers, induction motors, induction regulators and induction generators contain alternating-current magnets only.

A machine containing both direct- and alternating-current magnets may either give out or absorb magnetizing power. A machine containing alternating-current magnets only can also give out or absorb magnetizing power if provided with a suitable commutator. The use of such a commutator is, however, still unusual and the ordinary induction motors and most other machines containing alternating-current magnets have no commutators. A machine containing alternating-current magnets only, and without a commutator, can absorb but cannot give out magnetizing power.

Most alternating electric machinery is designed to have an approximately constant magnetization, therefore the magnetizing power is also approximately constant. The flow of magnetization to a transformer, induction motor or other non-commutating machine containing alternating-current magnets only, can be pictured as being constant at all loads for an ideal, perfect machine. For a practical machine the flow of magnetization will increase slightly with increasing load although the useful magnetization decreases slightly, the voltage being assumed normal at all loads. Increased voltage at any load increases the flow of magnetization, and decreased voltage decreases it.

PICTURES OF THE FLOW OF MAGNETIZING POWER

Magnetizing power being but an electrical variety of accelerating power, its flow may be shown by a similar picture. A ribbon may be drawn for it with a width equal to the product of the mean current by the mean potential.

Magnetizing power may be measured in the same units as accelerating or other power, though in electrical work magnetizing power is measured in kilovolt-amperes instead of in kilowatts. The two units are of the same dimensions, a kilowatt being the same as a kilovolt-ampere except that its application is limited by an additional convention that the current and pressure are in phase. It may be pointed out that it is equally important to distinguish between kilovolt-amperes of magnetizing power where current and pressure are in quadrature and kilovolt-amperes of apparent power where no determinate phase relation is implied.

Arrows may be placed on the ribbon to show the direction in which magnetization has been displaced. The demagnetizing of the field magnets of an alternator and the magnetization of the fields of an induction motor being proportional to the magnetizing power, and due to its flow, there is a natural basis for describing the flow as being from the point where demagnetizing takes place and to the point where the magnetism reappears. This displacement of magnetization, like the transfer of energy from flywheel to piston, is a transient change which occurs when the flow begins, but the displaced magnetization is only prevented from returning to its original state of equilibrium by the continuance of the flow of magnetizing power. The flow of magnetizing power is therefore not a cumulative flow, and if constant, does not further deplete the magnetization of the source from which it springs nor build up an indefinite amount of magnetization at its terminus.

THE INDUCTION MOTOR AND INDUCTION GENERATOR

Fig. 5 shows the flow of energy through an induction motor at varying loads. As previously mentioned, an induction motor contains alternating-current magnets only, and therefore must receive magnetizing power from some external source. The motor receives from the generator two independent kinds of power. The ordinary flow of energy through it is similar to that through a direct-current motor and requires no further comment.

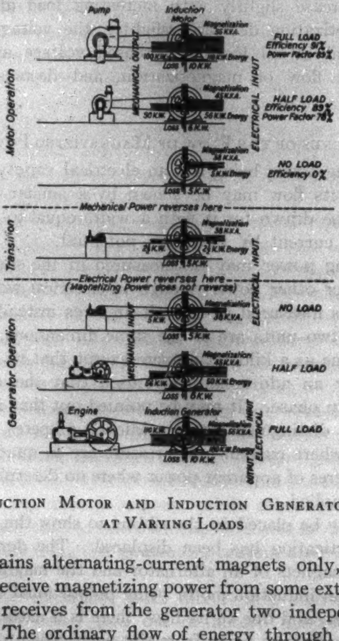
Pump
Induction Motor
Magnetization 55 K.V.A.
FULL LOAD
Efficiency 91%
Power Factor 83%
100 K.W.
110 K.W. Energy
Loss 10 K.W.
MECHANICAL OUTPUT
ELECTRICAL INPUT
Motor Operation
Magnetization 45 K.V.A.
HALF LOAD
Efficiency 89%
Power Factor 78%
50 K.W.
56 K.W. Energy
Loss 6 K.W.
Magnetization 38 K.V.A.
NO LOAD
Efficiency 0%
5 K.W. Energy
Loss 5 K.W.
Mechanical Power reverses here
Transition
Magnetization 38 K.V.A.
2½ K.W.
2½ K.W. Energy
Loss 5 K.W.
Electrical Power reverses here
(Magnetizing Power does not reverse)
Magnetization
NO LOAD
5 K.W.
38 K.V.A.
Loss 5 K.W.
Generator Operation
MECHANICAL INPUT
Magnetization 45 K.V.A.
HALF LOAD
56 K.W.
50 K.W. Energy
Loss 6 K.W.
Engine
Induction Generator
Magnetization 55 K.V.A.
FULL LOAD
110 K.W.
100 K.W. Energy
Loss 10 K.W.
ELECTRICAL INPUT
ELECTRICAL OUTPUT

FIG. 5—INDUCTION MOTOR AND INDUCTION GENERATOR OPERATION AT VARYING LOADS

The magnetizing power which flows into the motor and goes no further is the peculiar feature. The width of this power ribbon does not vary much from full load to no-load. Motors of different sizes take magnetizing power approximately in proportion to their horse power rating, though small motors take a somewhat greater proportion due to less perfect design. Low-speed motors take more than high-speed motors of the same rating, because the speed being low, the maximum torque must be high, and as the diameter of the armature is not increased sufficiently to maintain the same surface speed, a high torque requires more magnetic attraction and consequently more magnetism. Subject to considerable variation due to such causes, the figures shown may be taken as typical of any induction motor.

An induction motor like other motors is reversible in its function and may operate as a generator and is then called an induction generator.

Fig. 5 is extended to show the transition from motor to generator action. The operation of the motor as a generator amounts to a reversal of the flow of energy, precisely as with a direct-current machine.

However, *the flow of magnetizing power does not and cannot reverse.* An induction generator cannot produce magnetizing power. The induction motor is a reversible machine as regards the flow of energy but not as regards the flow of magnetization. This explains why one induction motor operated as a generator cannot operate another as a motor unless some other machine is also connected which is capable of furnishing the magnetizing power for both machines. It also shows why it may be advantageous to forego the simplicity of the ordinary induction motor and add a commutator so that the inward flow of magnetization may be reduced, eliminated or reversed.

SYNCHRONOUS MOTOR AND ALTERNATING-CURRENT GENERATOR

An alternating-current generator can operate as an alternating-current motor and is then called a synchronous motor. The synchronous motor differs from the induction motor in being completely reversible, that is, reversible as regards the flow of magnetization as well as of energy. Where an alternator transmits power to a synchronous motor there are three cases as shown in Fig. 6.

The simplest case is where, as in direct-current transmission, no magnetizing power is required. Each machine has its magnetization furnished locally by direct currents. The equality of excitation is indicated in the figure by drawing the exciters of the generator and motor as of the same size.

Above this case is shown the one where magnetization as well as energy is being transmitted from the generator to the motor. This indicates that the motor has insufficient magnetization, it is therefore said to be under-excited. The less the direct-current excitation of the motor, the greater the magnetizing power absorbed by it. This magnetizing power produces a useful magnetization in the motor just sufficient to supplement the inadequate direct-current magnetizaton. If the direct-current excitation decreases, the magnetizing power increases, so that finally, if the direct-current magnetization fails entirely, the magnetizing power alone may furnish approximately normal magnetization. A synchronous motor may, therefore, run without direct-current field excitation, in fact, this principle is used in starting synchronous motors and converters. Such an unexcited motor is similar to an induction motor but is so imperfectly designed for unexcited operation that it takes a much greater proportion of magnetizing power.

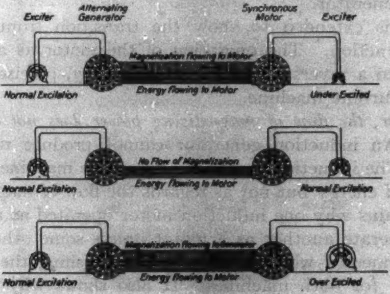
Exciter
Alternating Generator
Synchronous Motor
Exciter
Magnetization flowing to Motor
Normal Excitation
Energy flowing to Motor
Under Excited
No Flow of Magnetization
Normal Excitation
Energy flowing to Motor
Normal Excitation
Magnetization flowing to Generator
Normal Excitation
Energy flowing to Motor
Over Excited

FIG. 6—FLOW OF ENERGY AND MAGNETIZATION AT VARYING EXCITATIONS

An unexcited synchronous motor is, like an induction motor, reversible in regard to flow of energy and may be used as a generator. However, an unexcited generator or motor must absorb and cannot produce magnetizing power. Therefore, an unexcited generator cannot be used to run an unexcited motor unless there is some other source of magnetizing power adequate for both generator and motor.

At the bottom of the figure is shown the case where the motor has an excessive amount of magnetization or is over-excited. The magnetizing power now flows from the motor to the generator. The effect of this flow is to demagnetize the motor, the amount of flow being just sufficient to bring the magnetization of the motor down to equality with that of the generator.

The principle is, in fact, general, that magnetizing power demagnetizes the machine from which it proceeds and magnetizes the one into which it flows. Magnetizing power may, therefore, be imagined as a current or flow of magnetization from points of surplus to those of deficient magnetization. The surplus magnetization is to be found in those machines strongly excited by direct currents, the deficient magnetization in those weakly excited and more especially in transformers, induction motors and other apparatus having no direct-current excitation at all. Strong and weak excitation are of course only relative terms. If the excitation of a generator and a motor are equally strong or equally weak no flow of magnetizing power between them is necessary to preserve a balance. The voltage which a machine tends to have, due to its direct-current excitation alone, furnishes perhaps the simplest measure of the strength of excitation from the present point of view.

Where several alternating-current machines having direct-current excitation are connected together, the increase in the excitation of any one machine tends to raise its voltage but this tendency is counteracted by a magnetizing current which flows away from it to the other machines, demagnetizing it and magnetizing them. A considerable increase in excitation of one machine, therefore, produces a smaller though widespread increase in magnetization of all the machines. Conversely, a decrease in excitation of one machine causes an inflow of magnetizing power and a corresponding reduction in the voltage of the whole system. This condition holds whether the machines are all alternators or all synchronous motors or a mixture of the two. The function of the machine, whether generator or motor, is immaterial, the relative excitation is the essential thing.

The relative excitation of the machines (generators and motors) on a system governs the flow of magnetization and of that alone. The origin of the excitation is immaterial as regards the flow of energy; the excitation may all come from one machine, any one, or from all the machines in any proportion. As long as some source of adequate magnetization is provided the several machines may be driven as generators or operated as motors at will.

Consequently, increasing the excitation of one of two alternators will not shift load to the other and an alternator may continue to carry its full load even if its excitation is lost.

Raising the voltage at one power house will not shift load to another and the voltage may be higher at the delivery end than at the generating end of a transmission line.

It is true that such increasing of excitation and raising of voltage does shift the flow of power but it is the flow of magnetizing power only, not the flow of energy.

In every alternating-current system two kinds of power coexist and flow independently. The two kinds may flow in the same or in opposite directions. Either flow may vary without interfering with the other flow.

We may picture the variations in the two ribbons of power from a generator. The operator can with his right hand increase, decrease, stop or reverse the flow of the ribbon of energy by opening and closing the engine throttle or governor controller, while with the left hand he may similarly and independently control the ribbon of magnetization by raising or lowering the excitation by the field rheostat. The governor controller and the rheostat are the two handles by which to take hold of the two flows.

THE SYNCHRONOUS CONDENSER

Fig. 7 shows first an alternating-current generator at full load and over-excited. As the load is reduced, the energy flow decreases, stops and reverses just as previously shown for a direct-current machine. As the excitation is supposed to remain unaltered, the outflow of magnetizing power is practically unaffected by these changes of load by which a generator has become a motor. The transition stage between motor and generator operation presents the peculiarity that the machine though neither a motor nor a generator still produces magnetizing power. This feature is of such importance that the machine when so operating has a special name, being called a synchronous condenser.

The synchronous condenser can be used to produce the magnetizing power required for operation of induction motors or induction generators or for the starting of unexcited synchronous motors, or in fact for producing all or any part of the flow of magnetization required for a transmission system.

The amount of magnetization produced is under control, depending on the amount of excitation. The figure shows that with decreased excitation the flow of magnetizing power eventually ceases and that a further decrease reverses the flow. An under-excited synchronous " condenser " may be called a synchronous reactor.

TRANSFORMERS

Power consists of the product of two components, velocity and pressure. Either may be increased at the expense of the other and the power remains the same.

Mechanically, increase of pressure with decrease of velocity may be accomplished by gearing. In this graphical representation of power, where the power as a whole is shown but not its components, the transmission of power through gearing makes no change in the direction of its flow nor in the width of the stream except for the diversion of a small amount corresponding to the losses in the gearing.

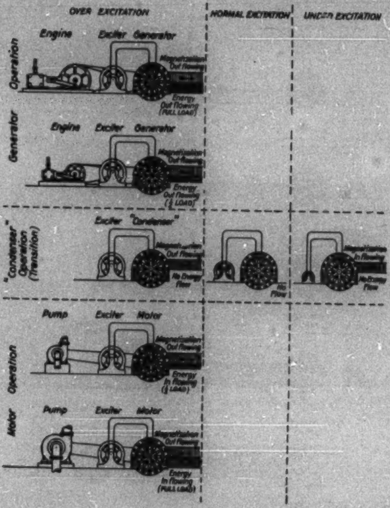
OVER EXCITATION
NORMAL EXCITATION
UNDER EXCITATION
Generator Operation
Engine
Exciter
Generator
Magnetization Out flowing
Energy Out flowing (FULL LOAD)
Engine
Exciter
Generator
Magnetization Out flowing
Energy Out flowing (½ LOAD)
"Condenser" Operation (Transition)
Exciter
"Condenser"
Magnetization Out flowing
No Energy Flow
No Flow
Magnetization In flowing
No Energy Flow
Motor Operation
Pump
Exciter
Motor
Magnetization Out flowing
Energy In flowing (½ LOAD)
Pump
Exciter
Motor
Magnetization Out flowing
Energy In flowing (FULL LOAD)

FIG. 7—SYNCHRONOUS CONDENSER OPERATION

Transformers are used for increasing electrical pressures with corresponding decrease in current. A transformer is therefore a kind of electrical gearing and power will pass through it with no change except a slight diminution to cover transformer losses.

Accelerating power can be geared up or down mechanically just as well as energy flow. Similarly, magnetizing power can be transformed as readily as energy flow. A transformer is therefore no barrier to the free and independent flow of the two kinds of power.

The electric transformers are a type of gearing corresponding mechanically to a direct-acting pump, the change of pressure being produced by alternating or reciprocating motion. The transformer, therefore, must itself receive a small amount of magnetizing power in order to work at all, but this is an approximately fixed amount and does not otherwise affect the free flow of magnetizing power through it.

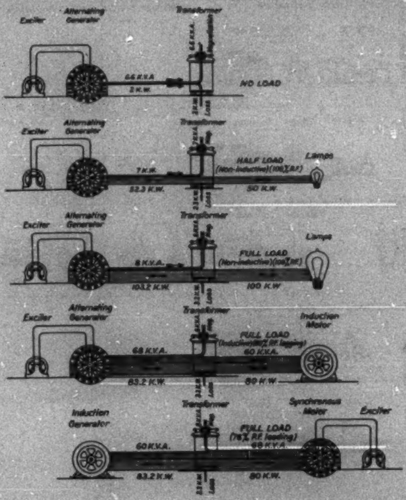
Exciter
Alternating Generator
Transformer
6.6 K.V.A.
Magnetization
6.6 K.V.A
2 K.W.
NO LOAD
2 K.W.
Loss
Exciter
Alternating Generator
Transformer
7 K.V.A.
Mag.
7 K.W.
52.3 K.W.
HALF LOAD
(Non-inductive)(100% P.F.)
Lamps
50 K.W.
2.3 K.W.
Loss
Exciter
Alternating Generator
Transformer
Mag.
Lamps
FULL LOAD
(Non-inductive)(100% P.F.)
8 K.V.A.
103.2 K.W.
100 K.W.
3.2 K.W.
Loss
Exciter
Alternating Generator
Transformer
Mag.
Induction Motor
FULL LOAD
(Inductive)(80% P.F. lagging)
60 K.V.A.
68 K.V.A.
83.2 K.W.
80 K.W.
3.2 K.W.
Loss
Transformer
Mag.
Induction Generator
Synchronous Motor
Exciter
FULL LOAD
(76% P.F. leading)
68 K.V.A.
60 K.V.A.
83.2 K.W.
80 K.W.
3.2 K.W.
Loss

FIG. 8—FLOW OF ENERGY AND MAGNETIZATION THROUGH A TRANSFORMER

The magnetizing power taken by a transformer is similar in characteristics to that of an induction motor, the principal difference being that the magnetic design of a transformer is much more perfect than that of an induction motor so that the proportion of magnetizing power taken is much smaller.

Fig. 8 shows the flow of power through a transformer. The transformer diverts from the energy stream a small branch which is consumed as transformer loss and from the magnetizing stream another small branch which magnetizes the core. Even at no load the transformer must receive these two small streams if it is active. Ordinarily both streams come from the same direction, that is, from the generator, but this is not essential, for when an induction generator drives a synchronous motor through the transformer the energy loss stream comes from the generator, the magnetization stream from the motor.

In a broad way generators and motors as well as transformers may be considered as a kind of gearing.

A generator, like a transformer or a gear, transforms the product of one motion and one pressure into an approximately equal product consisting of a different motion and a correspondingly different pressure.

Where both motions and pressures are mechanical the transforming device is called gearing, where one pair is mechanical and the other electrical it is called a motor or generator, and if both are electrical it is called a transformer.

APPARENT POWER

While energy flow and magnetizing flow can be considered to exist in the same circuit practically independently, there are not two distinguishable currents of electricity in the same wire. The currents and pressure of energy flow and of magnetizing flow combine into a single current and pressure. Neither the current nor the pressure alone shows any trace of the two components of which either may be considered to be built up. However, on comparing the composite current with the composite pressure it is found that the times of reversal are no longer either simultaneous or in quadrature. The effect on current and pressure of combining energy and magnetizing flow is to shift the relative time of reversal, or as it is ordinarily expressed, the phase is shifted. Conversely, it is found that whatever the difference in phase, the total effect of the current and pressure can be analyzed into two parts, one giving energy flow only and the other magnetizing flow only, and this forms one basis of the conclusion that energy flow and magnetizing flow are two fundamental kinds of power.

The product of current and pressure is power, the kind of power depending upon the phase. Disregarding the phase, which is often unknown, the product is called apparent power. When the phase of the two quantities is the same the apparent power is the same as energy flow, when phases are in quadrature it is the same as magnetizing flow. For intermediate phases apparent power consists of an energy flow component and a magnetizing flow component. It is found that the square of the apparent power is equal to the sum of the squares of the energy flow and the magnetizing flow.

This leads to the conclusion that if the ribbons representing energy flow are laid say horizontally and those representing magnetizing flow are turned vertically then a diagonal ribbon connecting them will represent the apparent power.

Fig. 9 shows how a flow of 80 kilowatts of energy and 60 kilovolt-amperes of magnetization gives an apparent flow of 100 kilovolt-amperes.

While apparent power is not itself a fundamental kind of power

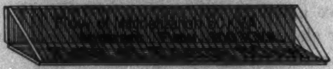

FIG. 9—APPARENT FLOW RESULTING FROM FLOWS OF ENERGY AND MAGNETIZATION

it is perhaps more readily measured than either energy flow or magnetizing flow, as it is only necessary to measure the current by an ammeter and the pressure by a voltmeter and multiply the result, without regard to the difference in phase.

It is also of importance because furnishing a measure of the size of generators, transformers, motors, etc., which must be used to transmit simultaneously the flow of energy and of magnetization.

POWER FACTOR

Power factor expresses the relation between energy flow and apparent power. It is the number of kilowatts of power delivered per kilovolt-ampere apparently transmitted.

When the power factor is fixed the relation between the magnetizing and energy flows is also fixed. If the power factor is constant the magnetizing and energy flows can only increase or decrease proportionally.

Fig. 10 shows the relation between the flow of energy and the flow of magnetization at various power factors. The two flows are equal for a power factor of $1/\sqrt{2} = 71$ per cent. With increasing power factors the proportion of magnetizing flow diminishes until it vanishes at unity power factor, while with decreasing power factors the proportion of energy flow diminishes and it becomes zero at zero power factor.

While the magnetizing power is relatively less at low than at high power factors an increase in power factor does not necessarily mean that the magnetizing power has decreased. Thus, in an induction motor, the power factor is higher at full load than at no-load, nevertheless the magnetizing power is also greater. The increased power factor results from a great increase in energy flow accompanied by a small increase in magnetizing power.

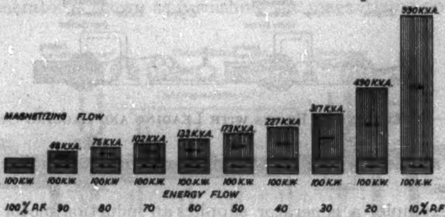

FIG. 10—RATIO OF MAGNETIZING FLOW TO ENERGY FLOW AT DIFFERENT POWER FACTORS

LAGGING AND LEADING CURRENTS

The terms lagging and leading indicate the relative directions of flow of the two kinds of power. If they flow in the same direction the current is said to be lagging, if in opposite directions, leading. If the current is lagging it may be changed to leading by reversing either but not both of the flows. If a synchronous motor is under-excited the current is lagging. Increasing the excitation makes the current leading because it reverses the flow of magnetization while the flow of energy is not affected. If, however, the excitation is not increased but mechanical power is applied to drive the motor as a generator, the current also becomes leading because the flow of energy has been reversed while the flow of magnetization is not changed. If the excitation is increased and mechanical driving power is also applied, the current remains lagging because both flows have been reversed. These effects are shown in Fig. 11.

BRANCHED CIRCUITS

Where a circuit branches, say from one generator to two motors operating at different power factors, the determination of the power factor of the generator from that of the motors looks rather complicated The same problem is extremely simple if viewed as the division of two kinds of currents, each into two branches.

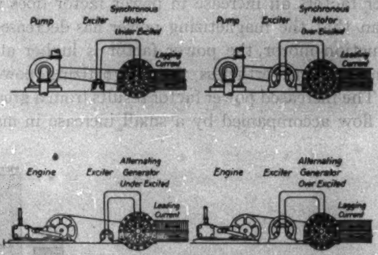
Pump
Exciter
Synchronous Motor Under Excited
Lagging Current
Pump
Exciter
Synchronous Motor Over Excited
Leading Current
Engine
Exciter
Alternating Generator Under Excited
Leading Current
Engine
Exciter
Alternating Generator Over Excited
Lagging Current

FIG. 11—DIRECTIONS OF FLOWS WITH LEADING AND LAGGING CURRENTS

For example, a generator supplies an induction motor taking 80 kilowatts at 80 per cent power factor lagging, and a synchronous motor taking 100 kilowatts at 98 per cent power factor leading. It is evident that the generator supplies the sum of 80 and 100 kilowatts, or 180 kilowatts, but it is not very obvious that its power factor is 97.6 per cent lagging.

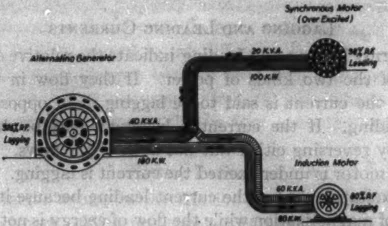
Synchronous Motor (Over Excited)
20 K.V.A.
98% P.F. Leading
100 K.W.
Alternating Generator
Lagging
40 K.V.A.
180 K.W.
Induction Motor
60 K.V.A.
80% P.F. Lagging
80 K.W.

FIG. 12—POWER FACTORS OF A BRANCHED CIRCUIT

Fig. 12 shows that this complicated relation of power factors is merely a roundabout way of saying that the induction motor takes 60 kilovolt-amperes of magnetizing power while the synchronous motor gives out 20 kilovolt-amperes, therefore, the generator must give out the difference, or 40 kilovolt-amperes.

From these elements a picture may be drawn of the flows of energy and magnetization in any transmission and distribution system. The ribbons show graphically the equality between inflowing and outflowing energy and between inflowing and outflowing magnetization. A single flow of energy may have associated with it two or more separate flows of magnetization as shown in Fig. 13. Here a synchronous condenser forms a local source of magnetization for the induction motors at the end of a transmission line, thus saving the losses of transforming and transmitting this flow as well as performing other useful functions. The generator is shown as furnishing the magnetizing power for motors in its vicinity. Water power transmission systems usually have little load at the generating end and there are indications that a normal method of operation of such systems is to have the source of magnetization at the receiving end. When the flow of magnetization is in the opposite direction to the flow of energy at full load, the voltage drop due to the load is decreased, and the regulation is improved.

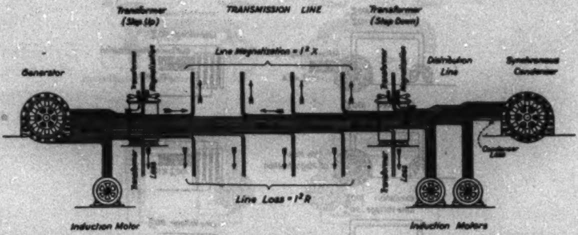
Transformer
(Step Up)
TRANSMISSION LINE
Transformer
(Step Down)
Line Magnetization = $I^2 X$
Generator
Distribution
Line
Synchronous
Condenser
Condenser
Loss
Line Loss = $I^2 R$
Induction Motor
Induction Motors

FIG. 13—FLOW OF ENERGY AND MAGNETIZATION THROUGH TRANSMISSION LINE

CHARGING POWER

The electric phenomena previously described are those which result from the storage of energy in an electric circuit due to magnetization. Energy may, however, also be stored in another form due to electric charging. Where the electricity is used in the form of alternating currents the electric charging current, like the magnetizing current, must transport this energy to the part charged and back to the source periodically. Charging power must flow to every part where there is electrostatic capacity. With charging power, as with magnetizing power, the current and potential are in quadrature. In fact charging power is the same as magnetizing power except that the direction of flow is reversed. That is, a kilovolt-ampere of charging power flowing south is the same as a kilovolt-ampere of magnetizing power flowing north. The single term, magnetizing power, is then sufficient for both. The choice of the term magnetizing power instead of charging power furnishes the basis of the convention which has been used in indicating the direction of flow of this kind of accelerating power.

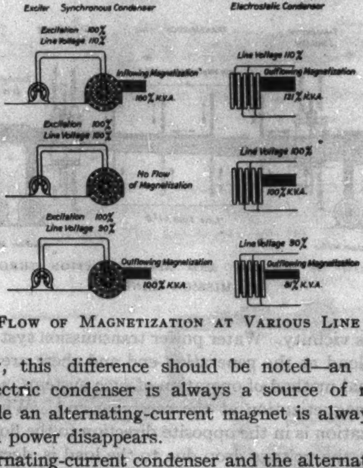
Exciter
Synchronous Condenser
Electrostatic Condenser
Excitation 100%
Line Voltage 110%
Inflowing Magnetization
100% K.V.A.
Line Voltage 110%
Outflowing Magnetization
121% K.V.A.
Excitation 100%
Line Voltage 100%
No Flow of Magnetization
Line Voltage 100%
100% K.V.A.
Excitation 100%
Line Voltage 90%
Outflowing Magnetization
100% K.V.A.
Line Voltage 90%
Outflowing Magnetization
81% K.V.A.

FIG. 14—FLOW OF MAGNETIZATION AT VARIOUS LINE VOLTAGES

However, this difference should be noted—an alternating-current electric condenser is always a source of magnetizing power, while an alternating-current magnet is always a sink in which such power disappears.

The alternating-current condenser and the alternating-current magnet are complementary.

The electric condenser, therefore, may be used as a substitute for the direct-current magnets of an alternator in furnishing the magnetization of a transmission system.

An alternator without direct-current field excitation may receive all needed excitation from an electric condenser, and an induction motor may operate as an induction generator receiving its magnetization from a condenser. These results are obtained in practise, though they are not the normal operating conditions on high-tension transmission systems.

A rotating machine structurally identical with an alternator or synchronous motor, but not performing any mechanical work, may furnish the magnetizing power for a system, in whole or in part, much as an electrostatic condenser would, and hence is called a synchronous condenser.

Fig. 14 shows the essentially different behavior of an electrostatic condenser and a synchronous condenser as the voltage changes. The flow of magnetizing power from an electrostatic condenser increases as the square of the voltage. Magnetizing power flows from a synchronous condenser only when the circuit voltage is below that corresponding to the excitation of the condenser. If these voltages are equal the synchronous condenser is neutral as regards magnetizing power. If the circuit voltage is higher, the synchronous condenser absorbs magnetizing power and ceases to be like a condenser, becoming similar to a reactor.

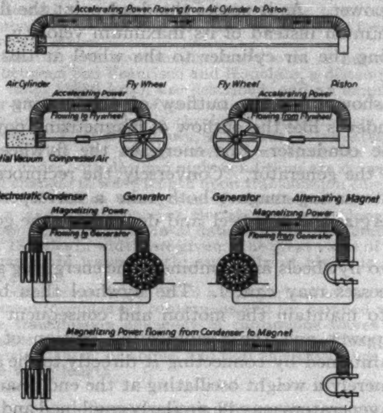
Accelerating Power flowing from Air Cylinder to Piston
Air Cylinder
Fly Wheel
Fly Wheel
Piston
Accelerating Power
Flowing to Flywheel
Accelerating Power
Flowing from Flywheel
Partial Vacuum
Compressed Air
Electrostatic Condenser
Generator
Generator
Alternating Magnet
Magnetizing Power
Flowing to Generator
Magnetizing Power
Flowing from Generator
Magnetizing Power flowing from Condenser to Magnet

FIG. 15—FLOW OF ACCELERATING POWER AND MAGNETIZING POWER IN OSCILLATING CIRCUITS

The phenomena due to charging power are not peculiar to electrical transmission. If the steam ports of an engine are permanently closed when the piston is in mid position in the cylinder it cannot be moved in either direction without compressing the air on one side and expanding that on the other side. If the engine shaft is rotated the piston will require a reciprocating force to overcome the air pressure and this force will be zero at midstroke and maximum at the dead point; that is, it is in quadrature with the motion. For a given direction of motion the direction of this force will be opposite to that which would be required for acceleration. This reversal of one component but not of both, reverses the direction of the power. Consequently, such an air-cushioned piston becomes a source of accelerating power. As it passes the dead point the flywheel now has its minimum instead of its maximum velocity. The effect of connecting the air cylinder to the wheel at this point is to energize it.

Fig. 15 shows that the outflow of accelerating power from an air cylinder is like the outflow of magnetizing power from an electrostatic condenser—one energizes the flywheel, the other magnetizes the generator. Conversely, the reciprocating piston and the alternating magnet both take a corresponding inflow and de-energize the flywheel and de-energize the generator, respectively.

If the two flywheels are combined, the energizing and de-energizing processes may cancel. The flywheel then becomes unnecessary to maintain the motion and consequent flow of accelerating power and the reciprocating motion of the piston may be maintained by connecting it directly to the air cylinder. It is then merely a weight oscillating at the end of an air spring.

The two generators may be similarly combined and eliminated, giving an electrical oscillating circuit of a magnet and a condenser.

Presented at the 307th meeting of the American Institute of Electrical Engineers, New York, April 9, 1915.

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CONTINUOUS WAVES IN LONG-DISTANCE RADIO-TELEGRAPHY

BY L. F. FULLER

Abstract of Paper

Ability to predetermine the probable normal daylight sending radius of high-powered radiotelegraphic stati ons is of prime importance in their design.

The theoretical transmission equations for both continuous and damped waves are discussed and the empirical formulas for the latter are given.

Experiments with continuous waves over a period of six months between San Francisco and Honolulu, a distance of 2100 nautical miles (3880 km.), are described, and an empirical formula for the calculation of probable sending radius with such waves is proposed. This is checked by experiments between Tuckerton, N. J., and Honolulu, 4330 nautical miles (8000 km.).

Curves giving the energy received at Honolulu from San Francisco under both day and night conditions are shown, and the effects of changes in wave length upon transmission efficiency are discussed. Evidence strengthening theories of the reflection, refraction and interference of Hertzian waves in long-distance transmissions, and experimental data showing interference bands not over 18 miles in width, are given. The great value of easy and rapid changes in wave length, especially at night, is apparent from the curves.

Final conclusions drawn from a comparison of the empirical transmission formulas for continuous and for damped waves are that the transmission efficiency of continuous waves is somewhat higher than that of damped waves on wave lengths of approximately 3000 m. or above, and that this advantage increases with the wave length.

Theoretical Features

THE comparative transmission efficiency of continuous and damped waves has been the subject of much discussion. Most experimental attempts to study the question have been over moderate distances and no difference has been observed until recently. Austin[1*] states that experiments of the United States Navy Department from the Arlington station, using a Poulsen arc for the generation of continuous waves and a 500-cycle spark transmitter for the production of damped waves, have shown that at distances of the order of 2000 nautical miles (3700 km.), or above, continuous waves are on an average superior.

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[*] **Reference numbers refer to the bibliography at end of paper.**

A theoretical analysis of the transmission of electromagnetic waves, either continuous or damped, over a perfectly conducting plane, was given by Sommerfeld[2] in 1909. Further treatment of the subject has been given by Poincairé[3], Nicholson[4], March[5], von Rybczynski[6] and Zenneck[7]. Certain experimental data over short distances have also been given by Duddell[8], Taylor[8] and Tissot[9].

In 1912, Eccles[10] gave a theoretical discussion of the propagation of electromagnetic waves in long-distance transmission around the curvature of the earth. His conclusions are strengthened by the United States Navy Department's tests of 1910 and 1913, recorded by Austin[1, 11], and by the Federal Telegraph Co. Poulsen arc, San Francisco-Honolulu tests of 1914, to be described herein.

The results of the Sommerfeld theoretical treatment of the transmission problem may be stated as follows for continuous waves:

$$E = 120\,\pi\,\frac{h_1\,I_s}{\lambda\,d}\sqrt{\frac{\theta}{\sin\theta}}\;e^{-\frac{0.0019\,d}{\lambda^{1/3}}} \qquad (1)$$

where E = effective electric amplitude in volts per km. of the electric field at a distance (d) from the sending antenna.

h_1 = effective height[12] of sending antenna in km.

I_s = current in amperes at base of sending antenna.

λ = wave length in km.

d = distance in km.

θ = angle at center of earth subtended by distance d.

It is assumed that the earth is perfectly conducting and that d is several wave lengths.

If the waves are damped, then on account of the wave train form of the oscillations,

$$E = 120\,\pi\,\frac{h_1\,I_s}{\lambda\,d}\,\frac{\sqrt{\dfrac{\theta}{\sin\theta}}}{\sqrt{1+\dfrac{\delta_1}{\delta_2}}}\;e^{-\frac{0.0019\,d}{\lambda^{1/3}}} \qquad (2)$$

where δ_1 and δ_2 are the decrements of the transmitter and receiver respectively.

Solving equation (1) for I_s the current in amperes at the base of the receiving antenna of effective height h_2 km. and of resistance R ohms, we obtain for continuous waves:

$$I_R = \frac{Eh_2}{R} = 120\,\pi\,\frac{h_1\,h_2\,I_s}{\lambda\,d\,R}\sqrt{\frac{\theta}{\sin\theta}}\cdot e^{-\frac{0.0019\,d}{\lambda^{1/3}}} \qquad (3)$$

and from equation (2) for damped waves:

$$I_R = \frac{Eh_2}{R} = 120\,\pi\,\frac{h_1\,h_2\,I_s}{\lambda\,d\,R}\,\frac{\sqrt{\frac{\theta}{\sin\theta}}}{\sqrt{1+\frac{\delta_1}{\delta_2}}}\cdot e^{-\frac{0.0019\,d}{\lambda^{1/3}}} \qquad (4)$$

This may be divided into four terms:

(1) $$120\,\pi\,\frac{h_1\,h_2\,I_s}{\lambda\,d\,R},$$

which is the Hertzian expression for the effective value of the current flowing through a resistance at a point in the equatorial plane of an equivalent oscillator of length $2\,h$ at a distance d.

(2) $$\sqrt{\frac{\theta}{\sin\theta}}$$

takes account of the curvature of the earth.

(3) $$\sqrt{1+\frac{\delta_1}{\delta_2}}$$

takes account of the damping at both transmitter and receiver and is therefore unity for continuous waves.

(4) $$e^{-\frac{0.0019\,d}{\lambda^{1/3}}}$$

corrects for the divergence of energy into the upper strata of the atmosphere due to the waves not following perfectly the curvature of the earth, and might be termed a "divergence factor."

All these theoretical equations are for a perfectly conducting earth surface. Von Rybczynski states that a slight decrease in conductivity will result in a slight increase in received energy, apparently due to a reduction in the divergence factor. A considerable reduction in earth surface conductivity, however, will result in severe loss, and an absorption factor[13] must be introduced. This is the case in most overland transmissions.

It is obvious, therefore, that theoretical transmission formulas must vary with the type of earth surface over which transmission is effected, and that empirical formulas derived from experimental data will likewise vary, the only certain uniformity possible in earth surface conductivity being over sea water. Atmospheric conditions affecting electromagnetic waves are so variable during the hours of darkness that it is only under normal day conditions that uniformity can exist. Hence, the only relatively uniform basis upon which theoretical and empirical formulas may be compared is for transmission over sea water under normal day conditions.

In 1911 Austin[11] gave the results of quantitative experiments up to 1000 nautical miles (1850 km.) from a spark transmitter at Brant Rock, Mass., and again[14] in 1914 with a spark transmitter from the United States naval radiotelegraphic station at Arlington, Va., up to 2000 nautical miles (3700 km.). These experiments with the damped wave may, according to Austin (loc. cit.), be expressed by the following semi-empirical formula:

$$I_R = 120\pi \frac{h_1 h_2 I_s}{\lambda d R} \sqrt{\frac{\theta}{\sin\theta}} \cdot e^{-\frac{0.0015\,d}{\sqrt{\lambda}}} \qquad (5)$$

The term $\sqrt{\frac{\theta}{\sin\theta}}$ may be considered as unity for distances of 2000 nautical miles (3800 km.).

The main point of difference between this and the theoretical Sommerfeld formula for the damped wave is in the last term, the divergence factor, $e^{-\frac{0.0015\,d}{\sqrt{\lambda}}}$ instead of $e^{-\frac{0.0019\,d}{\lambda^{1/3}}}$.

This makes long-distance radiotelegraphy much easier than theory would indicate and is probably due to a return of energy from the upper atmosphere by reflection or refraction, or both. Presumably, therefore, a convergence factor might be added to the theoretical formula. From many data available, especially those to be presented herein on the San Francisco-Honolulu sustained-wave experiments of 1914, it is probable that such convergence is considerably greater with continuous than with damped waves. No experimental data are available from any source on the effects of changes in decrement on transmission efficiency and divergence factor over long distances.

The foregoing covers briefly the theoretical equations of long-distance radio transmission for both continuous and damped waves and the empirical formula of Austin for damped waves. This formula (5) proves quite satisfactory for the ordinary calculations of practical work, and would indicate that a change should be made in the theoretical equations to account for the considerable increase in received energy noted, seemingly due to convergence; *i.e.*, a return to the earth's surface, near the receiver, of energy radiated into the upper atmosphere after leaving the transmitting station.

GENERAL DESCRIPTION

The following description of the San Francisco-Honolulu sustained wave tests of 1914 may be divided into two parts.

1. That dealing with the effects of wave length upon the strength of received signals. This has an accuracy which is satisfactory for comparative results, and probably averages within 10 per cent.

2. That part covering the derivation of a proposed empirical formula for sustained wave transmission. This has an accuracy below that which could have been obtained had the two stations involved not been handling commercial work, which necessitated the taking of experimental data at irregular intervals, and caused frequent interruptions. It is probably accurate within 20 per cent.

Thus all deductions based upon the relative value of received energy readings may be regarded as being considerably more reliable than those based upon actual received energy values.

It is believed, however, that all data are of sufficient accuracy for practical purposes and that the transmission formula for continuous waves may be satisfactorily used in commercial design.

DESCRIPTION OF PLANTS

The data presented herein were taken during the period of six months extending from January to June, 1914, inclusive. The range of wave lengths was from 3000 to 11,800 meters, and the distance of transmission 2100 nautical miles (3880 km.).

The stations were the San Francisco and Honolulu plants of the Federal Telegraph Co. Both were equipped with 100-kw. Poulsen-Federal arc transmitters rated on continuous d-c. input, although 40-50 kw. is the usual power employed.

Each had three guyed wooden towers, two 440 ft., and one 608 ft. in height, giving triangular flat top antennas of 0.010 mf. capacity.

At San Francisco the 440-ft. towers were 600 ft. between centers. The 608-ft. tower was 900 ft. from one, 1095 ft. from the other 440-ft. tower.

At Honolulu all towers were on 600-ft. centers, forming an equilateral triangle, and there was in addition the arc of approximately 135 degrees of an umbrella antenna, strung from the back side of the 608-ft. tower over shallow tide water. This accounts for the capacity of this antenna with the close tower spacing being the same as that at San Francisco.

The center of capacity at Honolulu was very close to 394 ft. (120 m.), while at San Francisco, due to greater sags, it was approximately 380 ft. (116 m.).

METHODS OF TAKING DATA

Antenna Currents were measured by hot-wire ammeters calibrated from a 100-ampere Hartmann-Braun unshunted hot band instrument used as a standard.

Wave Lengths were measured by a standard wave meter[15] employing a tikker and phones to indicate resonance.

Centers of Capacity were determined by mapping the triangular network of the antennas giving the height above the earth for various areas, and assuming a low capacity for the down leads.

Received Watts were determined by the shunted telephone method. The general procedure was identical with that used in the U. S. Navy Department tests of 1910 and 1913 described by Austin[11, 1] and was briefly as follows:

If the receiving telephones be shunted by a variable resistance, the incoming signal has an audibility of one when the shunting resistance is so adjusted that the dots and dashes can just be differentiated. The following relation then exists:

$$A_f = \frac{R + S}{S} \tag{6}$$

where A_f = audibility factor or number of times audibility.

R = impedance of telephones in ohms.

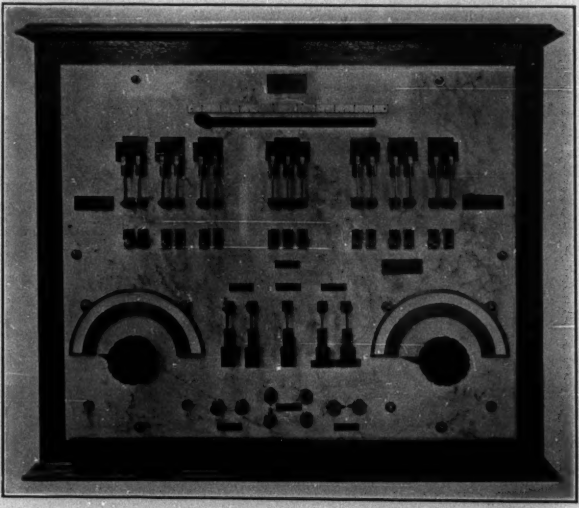
and S = impedance of resistance shunting telephones in ohms.

[FULLER]

EIGHT HUNDRED AND TWENTY FIVE-FT. STEEL TOWER AT TUCKERTON, N.J.

[FULLER]

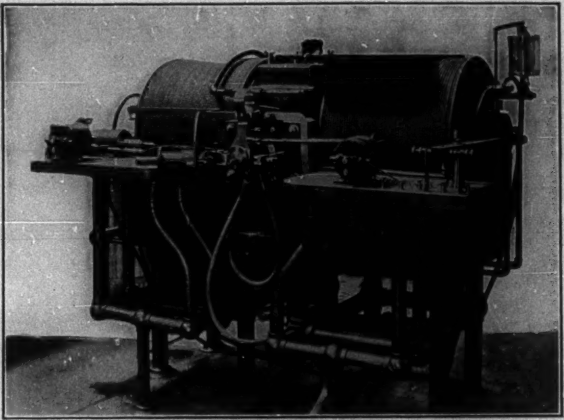
SIX HUNDRED AND EIGHT-FT TOWER AT SAN FRANCISCO



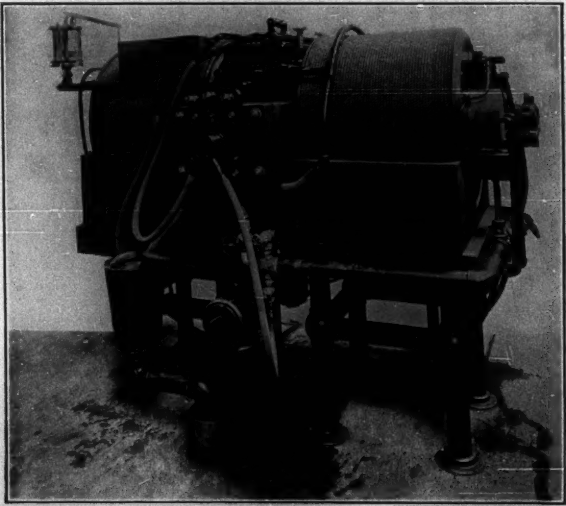
[FULLER]

TYPE OF RECEIVING APPARATUS USED AT HONOLULU AND SAN FRANCISCO DURING TESTS

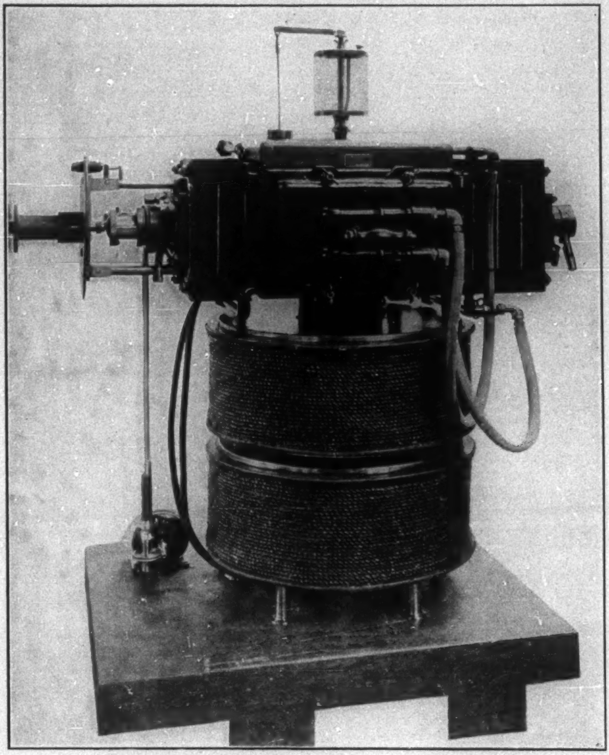
PLATE XLII.
A. I. E. E.
VOL. XXXIV, 1915


[FULLER]

FRONT VIEW 100-KW. POULSEN-FEDERAL ARC TRANSMITTER USED AT SAN FRANCISCO AND HONOLULU DURING TESTS


[FULLER]

BACK VIEW 100-KW. POULSEN-FEDERAL ARC TRANSMITTER



[FULLER]

THIRTY-KW. POULSEN-FEDERAL ARC TRANSMITTER

For the purpose of determining the received watts for a given value of resistance shunting the phones, or for a given audibility factor, another Poulsen-Federal arc station near by was used as a transmitter, and a thermo-couple and galvanometer were inserted in the antenna of the receiving station. These had previously been calibrated on direct current and indicated the received antenna current.

Measurements of the resistance of the antenna circuit, with the secondary of the receiver adjusted to resonance, were made throughout a range of wave lengths extending from 3000 to 10,000 meters, and the received watts for a known audibility factor were calculated by RI^2. These values of received energy were reduced to received watts for unit audibility. Using a rotary tikker and sensitive telephone receivers these results gave the relation

$$P = 3.2 \times 10^{-10} A_f \tag{7}$$

where P = received energy in watts and
A_f = audibility factor as defined above.

General Notes

Reference to the tabulated data shows the general average of signal strength obtained with the antenna current at the transmitter reduced to 35 amperes.

It was kept below 50 amperes in order that a minimum error might be introduced in correcting received current for a constant transmitting antenna current for all wave lengths. Preliminary investigation of this point showed that for transmitting antenna currents somewhat above 50 amperes the received current did not vary directly as the transmitting current[16] but fell off somewhat.

In order to eliminate as far as possible factors tending to cause questionable results, the antenna current in all tests was kept at such a value as to make it possible to correct received current with certainty to the values which would have been obtained had it been convenient to hold the transmitting antenna current constant for all wave lengths.

All data are for transmission with daylight over the entire path, except on a certain few night tests. With the exception of ten miles of bare hills approximately 1200 ft. in height at the San Francisco end, the path of transmission lies entirely over sea.

DISCUSSION OF CURVES

Figs. 1, 2, 3, and 4 show received energy as a straight-line function of the wave length. It is possible that during these tests the waves were subjected to refraction only and that the amount of energy received by reflection from the upper atmosphere was small, probably indicating stable day conditions.[17]

The data in Fig. 5 show a constant gain in received energy up to 7000 meters, with a second peak at 10,000 meters.

Fig. 6 is somewhat similar; again showing a maximum at 7000 meters, a minimum between 8000 and 9000 and a rise again at 10,000 meters.

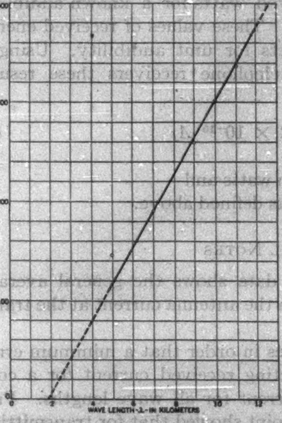


FIG. 1—HONOLULU TO SAN FRANCISCO, JAN. 25, 1914—SAN FRANCISCO TIME 1:05 P.M. - 2:55 P.M. $I_s = 35$ AMPERES.

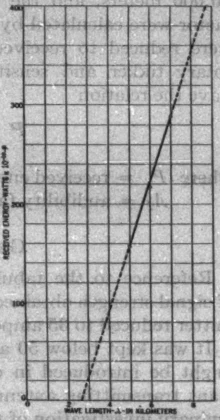


FIG. 2—SAN FRANCISCO TO HONOLULU, JAN. 25, 1914—SAN FRANCISCO TIME 9 A.M. - 12 M. $I_s = 35$ AMPERES.

Fig. 7 is also of this same general type. All three indicate a combination of day and night conditions with possibly partial interference on certain wave lengths, and addition on others, due to a combination of reflection and refraction phenomena.

Fig. 8 is a typical night curve showing a marked reduction in signal strength on certain wave lengths, probably due to reflection phenomena. When compared with Fig. 13, however, it will

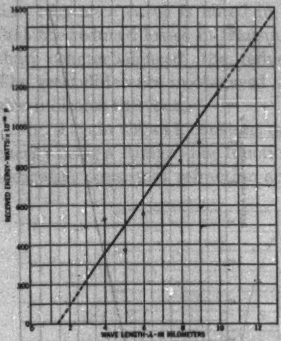


FIG. 3—HONOLULU TO SAN FRANCISCO, MARCH 1, 1914—SAN FRANCISCO TIME 10 A.M.-12 M. I_s = 35 AMPERES.

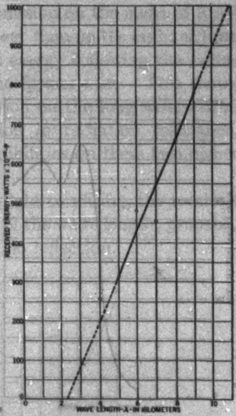


FIG. 4—HONOLULU TO SAN FRANCISCO, MARCH 8, 1914—SAN FRANCISCO TIME 11:44 A.M. - 12:03 P.M. I_s = 35 AMPERES.

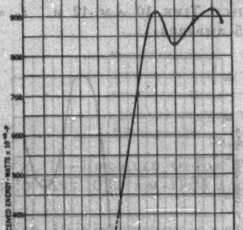


FIG. 5—HONOLULU TO SAN FRANCISCO, MARCH 8, 1914—SAN FRANCISCO TIME 3:08 P.M.-3:54 P.M.—I_s = 35 AMPERES.

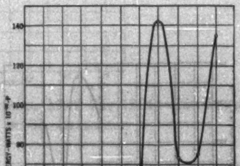


FIG 6—HONOLULU TO SAN FRANCISCO, MARCH 15, 1914—SAN FRANCISCO TIME 10:30 A.M.-12 M.—I_s = 35 AMPERES.

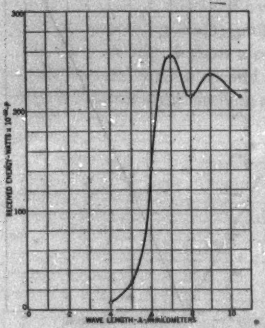


Fig. 7—Honolulu to San Francisco, March 15, 1914—San Francisco Time 3 p.m.-4 p.m. I_s = 35 amperes

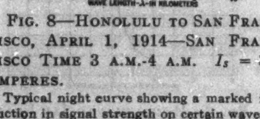


Fig. 8—Honolulu to San Francisco, April 1, 1914—San Francisco Time 3 a.m.-4 a.m. I_s = 35 amperes.

Typical night curve showing a marked reduction in signal strength on certain waves.

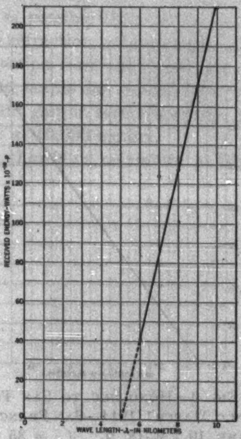


Fig. 9—Honolulu to San Francisco, May 3, 1914—San Francisco Time 10 a.m.-12 m. I_s = 35 amperes.

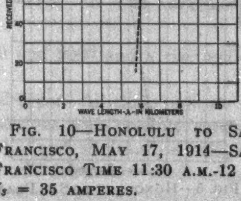


Fig. 10—Honolulu to San Francisco, May 17, 1914—San Francisco Time 11:30 a.m.-12 m. I_s = 35 amperes.

be noted that the efficiency of transmission on the night of April 1st must have been considerably lower than on the night of June 13th, since no reduction in received energy following the radiation resistance curve is noted in the former case. This shows that the reduced losses in transmission on the long waves more than counterbalanced the reduction in radiation resistance. The great difference in observed audibilities on these two nights also indicates this fact.

Fig. 9 again shows a constant daylight condition, the received energy being a straight-line function of the wave length, probably indicating consistent refraction and no reflection.

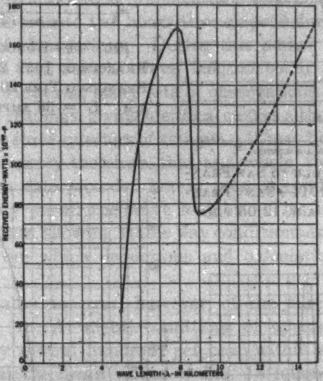


FIG. 11—HONOLULU TO SAN FRANCISCO, MAY 24, 1914—SAN FRANCISCO TIME 10:25 A.M.-11:25 A.M. I_s = 35 AMPERES.

Fig. 10 is interesting in again showing a maximum near 7000 meters; but the 8000- and 9000-meter waves show a decrease. Judging from the last two points on this curve, and from the behavior of curves in Figs. 11, 12, 14 and 15, it is probable that this curve, if continued, would show an increase in received energy.

Figs. 11 and 12 show a maximum at 8000 and 7000 meters respectively, a minimum at 9000 meters, and a decided rise at 10,000 meters. It is thought quite probable that at 14,000 and 16,000 meters, the double of 7000 and 8000 meters, other maximums might be noted. These are shown by dotted extensions.

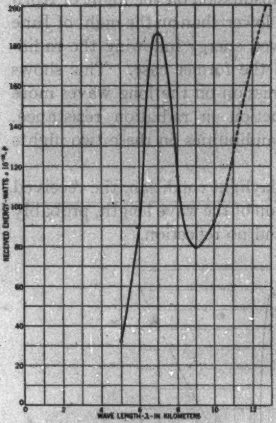


Fig. 12—Honolulu to San Francisco, May 24, 1914—San Francisco Time 11:25 a.m.-12:05 p.m.—I_s = 35 amperes.

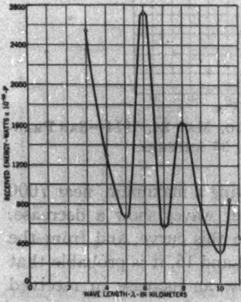


Fig. 13—Honolulu to San Francisco, June 13, 1914—San Francisco Time 2:45 a.m.-3:30 a.m.—I_s = 35 amperes.

Typical night curve showing marked reduction in signal strength on certain waves.

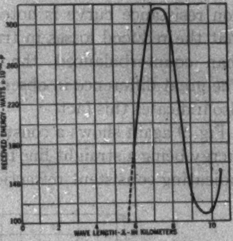


Fig. 14—Honolulu to San Francisco, June 22, 1914—San Francisco Time 10:30 a.m.-11:15 a.m. I_s = 35 amperes.

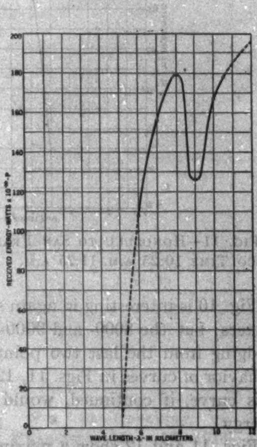


Fig. 15—Honolulu to San Francisco, June 28, 1914—San Francisco Time 10:45 a.m.-10:30 a.m. I_s = 35 amperes.

Fig. 13 is another typical night curve, similar to Fig. 8, showing a marked reduction in signal strength on certain waves. It is interesting to note that the average of these points gives a curve which follows the radiation resistance curve of the transmitting station, showing a falling off of the received energy in proportion to the reduction in the radiation resistance at the transmitter. For reasons given in the discussion of Fig. 8, the efficiency of transmission must have been very high and reflection phenomenon marked at the time Fig. 13 was taken.

Figs. 14 and 15 are typical examples of the unstable daylight class, probably indicating refraction, and in addition, reflection and a resulting interference upon certain wave lengths.

From a half-hour to two hours time elapsed during the taking of each set of observations. During this period the conditions of absorption for various wave lengths could have changed materially. However, many sets of observations are the results of two sets of readings, giving identical curves although separated by one-half to three-quarters of an hour. It may be assumed with reasonable accuracy therefore, that as a whole, the observations for any given date recorded herein present conditions existing simultaneously on all the wave lengths. This is undoubtedly true of the data showing stable day conditions and these are the only data from which deductions and calculations have been made.

It is probably not true, however, of the pure night curves, Figs. 8 and 13. At night, conditions of apparent absorption may vary by several hundred per cent within a few minutes. The fact that the mean values of Fig. 13 follow the radiation resistance curve, however, would tend to show that conditions were fairly uniform throughout the period during which its observations were made.

AN EMPIRICAL TRANSMISSION FORMULA FOR CONTINUOUS WAVES

The observed data are presented in the accompanying tables and from these the curves of the fifteen plates are drawn.

Calculations have been made from data taken from the curves *as drawn*. Only curves or parts of curves which show stable daylight conditions have been used. These are:

Fig 1. All waves
" 2. " "
" 3. " "
" 4. " "

OBSERVED DATA

CORRECTED TO $I_s = 35$ AMPERES

Fig. No.	Wave Length Meters λ	Received Energy Watts $\times 10^{-10}$ P
1.	5000	145.
	7000	190.
	9000	259.
	10000	301
	11000	336.
	11800	368.
2.	5000	157.
	6000	217.
	7000	288.
3.	3000	496.
	4000	531.
	5000	371.
	6000	557.
	7000	905.
	8000	829.
	9000	919.
	10000	1170.
4.	4000	255.0
	5000	312.0
	6000	480.0
	7000	454.0
	8000	660.0
	9000	778.0
5.	5000	429.0
	6000	707.0
	7000	911.0
	8000	830.0
	9000	886.0
	10000	919.0
	10500	886.0
6.	4000	7.8
	5000	14.6
	6000	53.6
	7000	142.0
	8000	73.3
	9000	75.2
	10000	135.0
7.	4000	7.8
	5000	27.2
	6000	142.0
	7000	255.0
	8000	215.0
	9000	237.0
	10500	214.0
8.	6000	1120.0
N	7000	1340.0
i	8000	788.0
g	9000	1100.0
h	10000	1100.0
t		
9.	6000	40.7
	7000	124.0
	8000	127.0
	9000	170.0
	10000	210.0
10.	6000	52.5
	7000	118.5
	8000	113.8
	9000	68.4
	10000	72.2
11.	5000	26.0
	6000	110.8
	7000	130.0
	8000	168.0
	9000	75.0
	10000	82.0
12.	5000	32.0
	6000	89.6
	7000	186.0
	8000	114.5
	9000	79.4
	10000	92.5
13.	3000	2540.0
	4000	1295.0
N	5000	668.0
i	6000	2720.0
g	7000	576.0
h	8000	1610.0
t	9000	743.0
	10000	320.0
	10500	842.0
14.	6000	179.0
	7000	310.0
	8000	292.0
	9000	127.0
	10000	111.0
	10500	151.0
15.	6000	107.5
	7000	156.0
	8000	179.0
	9000	126.0
	10000	167.0
	10500	178.0

Fig. 5. 5000-7000 meters
" 6. 6000-7000 meters
" 7. 6000-7000 meters
" 9. All waves

If in formula (**3**) the last term, the divergence factor $e^{-\frac{0.0019\,d}{\lambda^{\frac{1}{2}}}}$ be written e^{-Ad} and the whole formula be solved for A, we obtain

$$A = \frac{1}{d} \log e\, 120\, \pi \, \frac{h_1\, h_2\, I_s}{\lambda\, d\, R\, I_R} \sqrt{\frac{\theta}{\sin \theta}} \qquad (8)$$

Twenty-five separate calculations of A by the above formula have been made from data taken from the curves on wave lengths ranging from 3000 to 11,800 meters. From these it may be said that for continuous waves

$$A = \frac{\beta}{\lambda^{\sqrt{2}}} \qquad (9)$$

within the limits of error of these observations.

In the above equation the average of twenty-five values of β is 45×10^{-4}.

The exponent of λ shown in equation (**9**) holds consistently through all data, while β varies from day to day. The value given above was the average observed during these tests. The maximum noted occurred on March 15th on 6000 meters when β reached a value of 77×10^{-4}. The minimum noted was on March 8th on a 9000-meter wave when β dropped to 20×10^{-4}.

Substituting equation (**9**) and the above average value of β in formula (**3**), we obtain the following daylight transmission formula for continuous waves over sea water:

$$I_R = 377\, \frac{h_1\, h_2\, I_s}{\lambda\, d\, R} \sqrt{\frac{\theta}{\sin \theta}} \cdot e^{-\frac{0.0045\, d}{\lambda^{\sqrt{2}}}} \qquad (10)$$

where all factors are expressed as in formula (**3**).

No attempt has been made to give an average value of β for night work, since it may vary by many hundred per cent within a few minutes and a few hundred meters change in wave length may make a variation of the same order of magnitude. Figs. 8 and 13 illustrate these points. It is also obviously useless to attempt the approximation of β for day work during periods when partial night conditions exist. All such conditions usually tend to reduce the apparent absorption upon certain waves and increase it upon others. Hence in using formula (**10**) for the calculation of *average* sending radius and received signal strength, it may be considered safe to use the average value of β given above, provided the transmitting station has several waves at its disposal. If its available wave lengths are limited, however, it is liable, at times during which unstable day conditions exist, to be forced to transmit on a wave having poor transmission efficiency. With such stations it is obviously safer to use a value of β more nearly the maximum noted above for the calculation of *average* sending radius. The value to be used is naturally controlled to a great extent by the importance of the station, the quality of service required, and the geographical location.

During November and December, 1914, tests were carried on by the United States Navy Department from the Goldschmidt high-powered radiotelegraphic station at Tuckerton, N. J., to the Honolulu plant of the Federal Telegraph Company. Signals were transmitted in daylight the entire distance of approximately 4330 nautical miles (8000 km.), using a rotary tikker detector in receiving at Honolulu.

The antenna at Tuckerton consists of 36 wires attached to the top of a steel tower 825 ft. (250 m.) in height. The outer ends of these wires are attached to poles 40 ft. (12 m.) high arranged in a circle of 1500 ft. (450 m.) radius with the steel tower at the center. The wave lengths used by Tuckerton were 7400 and 10,000 meters. The shorter wave was never heard in Honolulu in daylight, but the longer was received consistently during the tests with daylight over the entire path of transmission. On the 7400-meter wave, both a Goldschmidt alternator and a Poulsen-Federal arc were used, but on the 10,000-meter wave only the arc was available.

Certain further checks on formula (**10**) are possible from these tests. These are as follows:

At San Francisco, approximately 2000 nautical miles from Tuckerton, the ratio of received currents for the 10,000- and 7400-meter waves was

$$\frac{I_{R\,10000\,m}}{I_{R\,7400\,m}} = 1.56 \text{ observed and } 1.67 \text{ calculated.}$$

This is primarily a check upon the $\sqrt{2}$ exponent of wave length and the constant β of 45×10^{-4} in the divergence factor.

At Honolulu a received current of 5.5×10^{-6} amperes on 10,000 meters was observed. The calculated value from formula (**10**) is 6.12×10^{-6} amperes.

On the 7400-meter wave from Tuckerton, formula (**10**) gives a value of received current below audibility and this is roughly checked by the fact that this wave was never heard until noon, Honolulu time, which was 5:30 p.m. at Tuckerton. This late in the day, normal conditions no longer exist and night conditions are beginning. The calculations are made from the following data:

I_s = 122 amperes on 10,000 meters and 100 amperes on 7400 meters
h_1 = 300 ft. = 91.5×10^{-3} km.
h_2 = 197 ft. = 60×10^{-3} km.
λ = 10 km. and 7.4 km.
d = 4330 nautical miles = 8000 km.
At Honolulu { R_{10000} = 150 ohms. High resistance due to close coupling, mediocre ground, and series receiving circuit.
R_{7400} = 135 ohms.
θ = 72.5 degrees.
A_f = 14.25 times audibility at Honolulu on 10,000-meter wave and zero on 7400-meter wave.
$P_R = 3.2 \times 10^{-10}$ watts for unit audibility.

No consistent difference was noted at San Francisco or Honolulu in the energy received from the alternator as compared with the arc when both were transmitting upon the same wave length and delivering the same antenna current.

The general conclusions to be drawn from the San Francisco-Honolulu and Tuckerton-Honolulu tests of 1914 are as follows:

(**1**) Under normal day conditions the comparative transmission efficiency of continuous waves is somewhat higher than that of damped waves on wave lengths above 3000 meters. The last term, the divergence factor of formula (**10**), compared with that of formula (**5**) shows this.

(**2**) The transmission efficiency of continuous waves generated either by a Goldschmidt reflection alternator or a Poulsen-Federal arc would seem to be the same.

(**3**) In transmissions over distances in the order of 4000 nautical miles, intervening land appears to be the equivalent of sea water, at least during the winter months. This may be due to the greater part of the received energy traversing the upper strata of the atmosphere.

(4) In the 15 curves shown in the figures, much evidence is found adding weight to the theories of refraction, reflection and interference upon certain wave lengths. These are further borne out by observations made at the Beach station of the Federal Telegraph Company, nine miles from the high-power plant described herein. Very frequently a wave length used by Honolulu, which is excellent at one, is useless at the other, and as atmospheric conditions change, conditions are reversed. This plainly shows interference bands not over 18 miles in width. Such phenomena are most apparent at night when reflection is pronounced.

(5) Ability to change wave lengths rapidly is of the greatest value in long-distance radiotelegraphy. Fig. 13 shows this to good advantage.

Formula (**10**) was derived from a distance of approximately 2000 nautical miles (3700 km.) and has been checked by the data presented herein for a distance of approximately 4330 nautical miles (8000 km.). It is believed that it is of sufficient accuracy for ordinary practical purposes and it is hoped it may be satisfactorily used in commercial design. It must always be borne in mind, however, that variations of 100 per cent or more may occur from day to day under seemingly identical conditions at both transmitter and receiver, and also that the formula was derived from data obtained from waves traveling over the waters of the North Pacific Ocean, which, as a rule, permits of greater transmission efficiency than is found in some other parts of the world.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the help received from his assistants, Messrs. R. R. Beal, E. B. Murphy and F. C. Ryan at San Francisco, and from Messrs. S. B. Maddams and H. L. Rodman at Honolulu.

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11. L. W. Austin, *Bul. Bu. Stds.*, Vol. 7, p. 315; 1911. Also *Jahrb. d. drahtl. Teleg.*, Vol. 5, p. 75; 1912.

12. The effective height of an antenna may be taken as one-half the length of the equivalent Hertzian oscillator and is equal to the height above the earth of the center of capacity of the antenna if the earth is perfectly conducting and large conducting masses are not near by to distort the electrostatic field. Often measurements of received energy at short distances upon receiving antennas of definitely known effective heights are necessary for proper determination.

13. J. Zenneck, *Ann. d. Phys.*, Vol. 23, p. 846; 1907. Also Lehrb. d. drahtl. Teleg., p. 297.

A. Sommerfeld, *Ann. d. Phys.*, Vol. 28, p. 665; 1909.

14. L. W. Austin, *Bul. Bu. Stds.*, Vol. 11, pp. 69-81; 1914 Also *Jahrb. d. drahtl. Teleg.*, Vol. 8, pp. 575-594; 1914.

15. G. W. Pierce, Principles of Wireless Telegraphy, p. 216.

16. A power overloading of the antenna and resultant atmospheric ionization in the vicinity of the transmitting antenna may be a factor in this phenomenon.

17. H. Parodi, *La Lumiere Elec.*, April 11-18, 1914. Also H. Barkhausen, *Elek. Zeit.*, April 16, 1914. Also W. H. Eccles and J. A. Fleming (10).

For general explanations of radio terminology, see report of Standardization Committee of Institute of Radio Engineers.

DISCUSSION ON "CONTINUOUS WAVES IN LONG-DISTANCE RADIOTELEGRAPHY" (FULLER), NEW YORK, APRIL 9, 1915.

Alfred N. Goldsmith: As Mr. Fuller has truly said, the paper will be of considerable assistance in enabling us in the future to proportion a transmitting set to the distance to be covered, at least under conditions such as he has mentioned; that is to say, transmission over waters similar in absorbing power to those of the North Pacific.

In my judgment, radio engineering is one of the most interesting branches of electrical engineering imaginable; in fact it is unique in that we are compelled to employ novel units of time and space. The unit of distance for our purposes is logically the distance which an electromagnetic wave travels in a second. We deal with almost incredible velocities, namely, those of the light waves themselves. However, the electromagnetic waves employed differ from the extremely minute light waves in that the wave length ranges from several hundred feet to five or six miles, or more, as indicated by Mr. Fuller.

We deal here with frequencies quite outside of the range normally employed in a-c. engineering. They run from 15,000 to 20,000 per second for our long wave, well up into a million or more cycles per sec. All of these unusual conditions of working lend to radio engineering a certain fascination, which never fails to keep men in that field, once they enter it. There is hardly any possibility of their leaving it thereafter.

To pass to continuous wave transmission, it is extremely interesting to note that sustained wave transmission is practically the meeting ground of ordinary electrical engineering and the radio engineering of the present. We are dealing here with true alternating currents in the antenna, generated by methods which are or should be familiar to every electrical engineer. They may be handled, received, detected, neutralized or manipulated, in general, exactly as are the ordinary alternating currents used in engineering, and the laws which govern 60-cycle currents govern them equally well. That is something which cannot be said, without mental reservation, when we come to the highly damped wave train, used in the older spark radiotelegraphy. Furthermore, the devices employed to produce continuous waves are of a type easily comprehensible to every skilled electrical engineer; for example, a device like the Goldschmidt alternator, which is, as Professor Kennelly has aptly termed it, nothing more than "a nursery for higher harmonics." It is a device in which, instead of eliminating these troublesome visitors of higher frequency, they are nursed and brought to resonance and finally radiated from a properly arranged electrical system.

We have with us this evening a gentleman who has been very prominent in the production of alternators which produce incredibly high frequencies, from 100,000 to 200,000 cycles per sec. His work in this field has been of a pioneer character, and later on it will be a pleasure to hear what he has to say about sustained waves. Some of the alternators designed by him are provided with a rotor having a rotational speed of 20,000 rev. per min., with 800 to 1200 poles; and to load them, they are directly connected to a capacity and a resistance of proper value so that full energy may be drawn from them. Such alternators are of interest to the electrical engineer, if only to emphasize the fact that not all alternators need to be connected to a water rheostat in order to absorb their output.

In connection with the use of sustained waves, certain new effects have for the first time become of interest and prominence. The first of these is unquestionably that of reflection or interference of the sustained wave. I recall some time ago hearing Dr. de Forest present a lucid description of this phenomenon before the Institute of Radio Engineers. He was at that time with the Federal Telegraph Company. The results he presented were perfectly clear so far as they affected the reflection of waves.

We deal here with a vast out-door laboratory. Imagine waves thousands of meters long, which strike cloud layers, or conducting layers. They are reflected downward and interfere definitely with waves which have pursued a shorter path directly along the surface of the earth. Clearly there will be points at which waves of a certain length are destructively interfered with, and consequently signals will become quite inaudible; and yet at points situated differently, without interfering radiation from the reflecting layer, the same waves may produce powerful effects. We have here a highly novel reflecting effect, one worthy of study, and which may lead to important contributions to our knowledge of the nature of the upper layers of the atmosphere.

The sustained wave methods of radio transmission have also led to the development of new methods of reception. They have led to the introduction of that curiously mysterious device the tikker, particularly the rotary tikker. This instrument consists of a metal wire resting on a rotating metal wheel. It acts as a commutator which periodically discharges a condenser, this condenser being charged slowly by the incoming energy. The discharge passes through the telephone receiver and produces the received signal. We know that these effects exist; but it is not clear why only certain combinations of metal should be satisfactorily operative. I trust that some light will be shed on these points in the near future.

There is a device known as the tone wheel, used by the Goldschmidt company, which is nothing more nor less than a carefully designed commutator. This interrupts the incoming energy at a frequency slightly different from the incoming frequency, and produces something which is not quite a beat phenomenon, but which fortunately renders the incoming energy available to deflect the telephone diaphragm at an audible frequency. This would be a device of no great use with damped wave trains. And finally, the use of sustained waves has led to the development of that extremely efficient method of reception known as the heterodyne system of receiving, wherein the incoming energy which, of course, is nothing more nor less than a normal radio-frequency alternating current, is caused to produce beats with the locally generated alternating current. These beats are of audible frequency, and frequently the energy represented by the beat may be, and practically always is, much higher than that of the incoming energy itself. We thus have an extremely efficient device. On a small scale, it is nothing more nor less than the beat effect produced by two alternators which are not quite in step. The synchronizing lamp flickers up and down, and at a frequency less than that of either of the alternators. Similarly, the telephone diaphragm moves to and fro at a frequency which is the difference between that of the incoming energy and that of the locally generated energy, and much lower, therefore, than either. We have, consequently, a device that is efficiently possible only when we are using sustained waves.

The arc as a generator is a device that some time ago seemed to be practically hopeless. No one supposed that so erratic and irregular a device as an arc could be used to produce a steady flow of very high frequency alternating current. Every one knows the arc has the negative characteristic; that a slight increase in voltage will produce an increase in current, and vice versa. It is essentially unstable, and series resistance will be required in general to maintain the stability of an arc, unless a special form of d-c. generator be used with it.

It is, therefore, a scientific *tour de force* that we have been able so to build and control arcs by circuits connected to them that they have now become satisfactory and reliable generators of considerable amounts of sustained energy. Of course, in the radio station, 50 kw. is a large amount of energy.

The arc apparatus is distinguished by unusual simplicity. When looking at the picture of the arc in the paper, one looks at practically all there is of the station except a few switchboards, a key, and a loading antenna inductance. The station is simple, readily worked, and easily accessible in all its parts.

We can imagine the predicament in which Mr. Fuller would have been had he been forced to change his transmitting wave lengths rapidly, using the very high speed radio-frequency alternator. In slowing down or speeding up such an alternator hastily, dangerous strains would have been developed. This brings up a point of interest to those who desire to apply radio apparatus to military purposes; namely, that it is desirable to avoid interference by the enemy's transmitters, or to interfere with them, if desired. It is also valuable from the commercial point of view, in that if a certain wave length is found to be unsuitable for transmission at a given time, it may be changed; and consequently the possibility of a rapid change of wave length is extremely valuable. Those who are going to work on the production of sustained oscillations should bear in mind that one of the prime desiderata of a generator of this type is the possibility of rapidly changing the wave length.

In this connection, Mr. Fuller has brought out the "sunrise effect", which is of great interest to us. Somewhere between two stations which are widely separated there may be a dividing surface between the light and darkness. In an admirable paper presented to the Institute of Radio Engineers some time ago, Professor Kennelly brought out the fact such a surface of darkness and light would act as a fairly good reflector for waves which strike it. It is a region where there may be considerable ionization of the upper layers of the atmosphere, due to the sunlight falling on one side. In consequence, we may expect to find a sudden diminution of received energy as the sun rises and the ionization boundary layer sweeps along between the stations, and this effect is found to exist. This leads to an interesting speculation of another sort. If the atmosphere, indeed, produces such great changes in transmission, is it not possible that only the earth's atmosphere and ground have properties which make radio transmission over long distances possible? The earth, in effect, is a slightly conducting sphere. A non-conducting layer of air surrounds it, and then above this are upper layers of air which are certainly fairly good conductors, being at approximately the same pressure as exists in a normal Geissler tube. Above this, there is a region of absolute non-conductivity.

The boldness of the early experimenters in this field is to be commended, particularly the experiments at Newfoundland, where Mr. Marconi attempted to receive the *S* signals sent out from Poldhu, near Cornwall, England, at a distance of several thousand miles. Such boldness was commendable, because there was little reason to expect that energy would follow the curve of the earth. To-night we have experiments described where energy travels along the earth in spite of the fact it might have been radiated off into space. It is obvious that such waves must have their feet attached in some way to the earth, or are reflected from the upper layers of the atmosphere.

Obviously, we have a peculiarly fortunate arrangement of conducting layers on the earth, so proportioned physically that long-distance radiation is possible. The great degree to which radio transmission depends on these physical conditions leads us to wonder whether the earth is not the only planet on which long-distance radio communication is possible.

J. Zenneck: I should like to call your attention to the following points. The formula on which all measurements of Mr. Fuller are based is equation (**7**):

$$P = R I^2 = 3.2 \times 10^{-10} A_f$$

It indicates that the audibility factor A_f in Mr. Fuller's device was proportional to the received watts. Now the audibility factor is proportional to the current in the unshunted telephone circuit, supposing that the main current in this circuit is not changed by shunting the telephone. Therefore, in Mr. Fuller's arrangement the telephone current must have been proportional to the received watts.

Mr. Fuller used as a detector, a tikker. Therefore we should expect that the telephone current be proportional to the received current I itself, but not to the received watts and therefore not to the square of the current. I should be very much obliged to him if he would kindly give us more details regarding this fundamental point.

Mr. Fuller by comparing his results with those of Dr. Austin comes to the conclusion that the divergence of the continuous waves used by himself is smaller than the divergence of the damped waves used by Dr. Austin.

Now of course two sets of measurements can only be compared if they are made under the same conditions.

Identity of conditions in wireless work in the first place means identity of atmospheric conditions. As the values of Mr. Fuller vary very much from day to day (see Figs. 4, 6 and 9 of his papers) it would be a little embarrassing to say at what time the atmospheric conditions over the Pacific in 1914 have been identical with those over the Atlantic in 1910 and 1913, when Dr. Austin made his experiments. I fully agree with Mr. Fuller that in such cases nothing else can be done than comparing the average values of the measurements. But I think that he will agree with me that this is not what is really wanted.

Further, in all cases where the waves are passing from the surface of the land to the surface of the sea or in the opposite direction, there must be a reflection of the surface waves, because the dielectric constants and the conductivity of solid ground and sea water are quite different. Therefore, two measurements are only comparable, if in both the reflection takes place in the same way. This condition is very troublesome too, as we do not know anything about the laws governing this reflection of surface waves.

Finally, as the divergence factor largely depends on the wave length, only such observations as are made with the same wave length should be compared. Now Dr. Austin made his experiments with wave lengths up to 4000 m., and Mr. Fuller with wave lengths from 3000 to about 10,000 m. Therefore their measurements are only comparable between the limits of 3000 to 4000 m. I have plotted curves, using the wave lengths as abscissas and the values of the exponent $\frac{\beta}{\lambda^n}$ of the divergence factor as ordinates. In Fig. 1, curve A represents the values based on Dr. Austin's empirical formula and the curve F those derived from Mr. Fuller's empirical formula (the curve S is that according to the theoretical formula of Professor Sommerfeld). You see that within the limits from 3000 to 4000 m. of wave length the values derived from Dr. Austin's equation and those corresponding to Mr. Fuller's formula agree excellently.

If we were justified in extending an empirical formula beyond the limits within which it is verified by experiments—for instance, Dr. Austin's formula for wave lengths above 4000 m.—we should get the dotted line A, and we should really come to the conclusion, as Mr. Fuller does, that the divergence factor for his undamped waves is smaller than that for Dr. Austin's

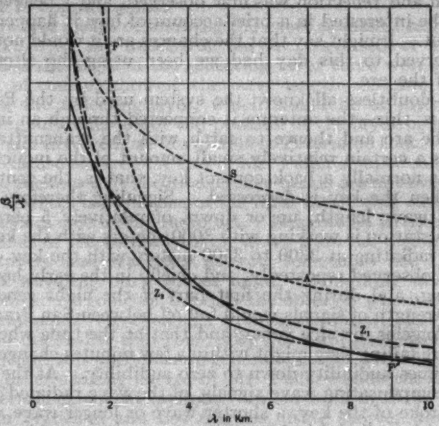

FIG. 1

damped waves. But if we would extend Mr. Fuller's formula on values below 3000 m. (see the dotted curve F), *we should get just the contrary result.*

Under these circumstances it seemed to me more attractive to combine the results of Dr. Austin and Mr. Fuller than to point out any discrepancy between them. This may be done in various ways: Putting the divergency factor $= e^{\frac{-0.0019}{\lambda^{\frac{1}{2}}\sqrt{3}}d}$ we get the dash curve Z_1, or using as divergency factor the simple term $= e^{\frac{-0.0019}{\lambda}d}$, we get the dash-dotted curve Z_2. Both curves, especially the first, agree fairly well with the results of Dr. Austin and Mr. Fuller at the same time.

Lee de Forest: Without wishing in any way to violate our neutrality, I might say that this paper tonight should make Americans who are at all interested in the progress of the radio art feel very happy. The work which Dr. Austin and Mr. Fuller have done stands alone to date. There have been no observations of the sort made anywhere else in the world to my knowledge. Of theoretical formulas we have had a plenty, but they lack the interest which an empirical formula based on actual observations of such a thoroughly practical character as this possesses.

It was my good fortune to be with the Federal Telegraph Company at the time this matter of the interference bands and absorption and reflection was first observed, and I believe that you may be interested in a brief account of how it happened to come about. I might say that the chances are it would not have been observed to this day had we been using the alternator instead of the arc.

As you doubtless all know, the system used by the Poulsen company is this—the antenna is connected through an inductance to the arc and thence to earth, with the transmitter key put across a certain relatively small amount of the inductance. The key is normally a back contact key, that is, the contact is broken when the key is depressed. Signaling therefore is by change of wave length, up or down, of relatively 5 per cent. Suppose a station is working with 3000 meters with the key up, it will be radiating at 3300 to 3500 meters with the key down.

We had observed repeatedly, and chiefly in the early hours of the evening, and during the first part of the night generally, that the strength of signals would fall off between San Francisco and Los Angeles, or vice versa; and that at the time when the signals were failing they might within a few minutes change from 40 or 50 times audibility down to zero audibility. At the same time the compensating wave signals, of the wave radiated on the upward stroke of the key, a shorter wave or longer wave, would be heard with undiminished intensity or even increased intensity. In order to hear the compensation wave signals it was merely necessary to change the " tuning " adjustment of the receiver slightly. It was easy to make such observations, and time and time again the operators observed these facts. In such cases they merely told the distant operator to change his wave length, which he did by cutting in a different amount of inductance on the transmitting helix. Or they sent their messages on the commutation wave until the signals came in loud, until such a time as these signals would in their turn begin to fade, when they would then find the compensation wave signals coming in loud, and change back again to the original wave lengths. Such experience became the common talk, although we were quite at a loss to explain the phenomenon. It is simple now to understand it, but at that time it was a tremendous puzzle. As we had a great many fogs at that period, we thought it might be due to absorption, but could not understand why a wave three thousand meters long should be largely absorbed, while a wave thirty-three hundred meters in length was not, in the same degree. This phenomenon of the huge interference bands in the upper atmosphere forced itself upon us, and all of our observations have established the truth of the explanation more and more.

The interference effect is easily understood. If we suppose an upper reflecting layer parallel to the earth's surface, and from twenty to one hundred miles above it, then the energy which travels along the earth's surface is, at certain distances from the transmitter, in phase with the energy reflected downwards from some definite zone of this upper layer. Likewise at another point where the difference in the lengths of the two trajectories is one half wave length greater or less than before, the two energies will be in opposite phase.

If we had means of knowing the exact points of reflection, for example, if at the middle of the arc traversed or any point, provided the angle of the reflecting layer there were known, we could, of course, knowing the wave length, compute the elevation of the reflecting layer, which would be of interest. Not knowing anything about the position of the layer or layers, nor the angles involved, we are unable to determine that.

The clause towards the end of Mr. Fuller's paper calling attention to the fact that the interference bands are not over eighteen miles in width is to me one of the most interesting statements in the physics side of the radio art. Imagine an invisible aurora, the bands of the aurora hanging down from the regions of upper atmosphere and wavering as you sometimes see the visible aurora wavering on a winter night. Something akin to that phenomenon is going on, but only the observer who is listening to the undamped wave signals from a distant wireless telegraph station can realize that this really beautiful phenomenon exists. In daylight this phenomenon generally ceases, although I observe these other striking curves of Mr. Fuller's show the same effect, to a certain extent, in daylight. In our work in 1910, '11 and '12 at San Francisco and Los Angeles, using shorter wave lengths over shorter distances, these daylight effects were seldom observed. They are most prominent at night when the altering meteorological conditions of daylight merging into darkness bring down these ionized strata or bodies of conducting air into a great variety of shapes and angles.

Only those who have worked frequently with the undamped wave method of transmission can realize the importance of being able to change the transmitted wave length at an instant's notice, in order to maintain anything like reliable communication.

While we are observing these things and plotting curves of the actual interference phenomena in this country, I have been astonished to see in the foreign papers, notably in the columns of the London *Electrician*, long series of disputes between distinguished solons, on the theoretical possibility of this reflecting or refracting layer. One says it conceivably might exist, and another says that mathematically it cannot exist, and here it is as well and as indubitably established as is the fact that we can transmit messages through space at all.

A. J. Hepburn: The importance of Mr. Fuller's work embodied in this paper is obvious in view of recent developments in the art and the almost universal recognition of the superiority of the undamped wave for long-distance communication. The experiments described are the most thorough and conclusive that have come to my attention and it seems to me that this paper is the most valuable contribution to the science, as regards the particular phase treated, that has been made since the publication of the Austin formula. In the somewhat hurried consideration I have found it possible to give to this paper, there has appeared to be nothing to criticize as regards conduct of the experiment, analysis or deductions, *provided that one does not go back of the fundamental assumptions*.

The number of radio engineers engaged principally with the problems of long-distance communication, to whom such work as this is of special importance, is but a small proportion of the total number; and the number of those engaged in a purely executive capacity with the technical direction of a large radio system is smaller still. When one of this small number finds himself in a position absolutely unfettered by allegiance to any system, or the necessity of protecting investments in patents and manufacturing plants, and responsible only for producing the most efficient and the most economical results by any means known to the art, it may be conceded that his point of view is likely to be unusual. If the following remarks seem to question some of the most authoritative pronouncements in the matter I trust that the unusual point of view will be taken into consideration.

Briefly, I believe that we need a transmission *theory* more than we need a transmission *formula*. Almost any sort of suggestion as regards possible factors affecting transmission receives a respectful hearing in the present state of variant opinions on that subject, but all efforts to evolve a more accurate formula are made very conservatively, not to say gingerly. This is curious in view of the fact that the formula is but the mathematical statement of the theory. I ascribe it to the restraint imposed by the great weight of authority behind the mathematical work that has been done.

I believe that there is promise of most valuable progress toward the establishment of a complete theory in a course of experimental work such as that which has been contemplated by the Navy Department for several years, but which has been prevented by the pressure of routine work. The plan contemplates the use of the station at the Washington Navy Yard as a transmitting station and the stations at the Bureau of Standards (6 miles distant) and that at Annapolis (23 miles distant) for measurements of received energy. Starting with the Austin formula as a trial basis each separate factor would be independently investigated, as well as some other possibilities that do not appear in that formula, such as decrement and reflection. For example: The height of the transmitting antenna would be systematically varied while all other factors are kept constant; then the height of the receiving antenna; then the antenna amperes; then the wave length; then the decrement due to added ohmic resistance; then the decrement due to increased radiation resistance, that is, different forms of antennae; and so on. These experiments would of course have to be repeated in a different locality and over greater distances to determine the constants that might appear, but operation at close range where the utmost nicety of measurement is possible would be the first requisite. This is a suggestion rather than an outline of the work planned. If it illustrates sufficiently well the method of attacking the problem, the ramifications of the work will be self-evident.

I cannot but feel that the result of such experimental work would lead to some notable changes in the complexion of the present transmission formulas. In this hasty comment I have no opportunity to submit anything approaching a full statement of the reasons that have led to this point of view, but I would call attention to the few following points, not as presenting any ordered argument but simply as significant in themselves.

(*a*) The remarkable instances of unusual communication, familiar to every head of a radio station, which do not accord with any known theory. For every instance explainable on the theory of reflection, for example, one may be cited in contradiction; and the same as regards wave length, land or sea effect,etc. A single discrepancy of this nature is sufficient ground for investigation.

(*b*) On the theory of an upper conducting layer of atmosphere to which the waves are "attached" as to the earth, how conceive reflection from that layer more easily than from the earth itself?

(*c*) Mr. Fuller's statement that the received energy did not always increase with the antenna current above a certain limit is very significant in view of many observations on this head by others.

(*d*) The indication of interference bands noted by Mr. Fuller is rather striking, but would not this phenomenon of itself invalidate the quantitative measurements founded on wave length taken at a single fixed station?

(*e*) I have not had an opportunity to calculate by Mr. Fuller's formula the relative increase of received energy due to sustained oscillations over that given by Austin's formula for the same radiation in the form of wave trains, but my impression is that the consistent results of actual day-to-day work would show the superiority of the undamped wave to be very much greater than indicated by the formula. This, of course, independently of the more efficient receiving apparatus which is generally used for undamped waves.

(*f*) We cannot imagine the conductivity of the earth or sea varying to a great extent, certainly not commensurately with the wide variations noted in received energy. Is this factor then of small importance? Every theoretical writer and every practical engineer accords it first place in his consideration of the subject. Whatever its importance, it seems to deserve a place in the transmission formula. It is certainly subject to quantitative measurement.

Considerations of this nature might be added at great length. The point I want to make is that if we limit our efforts in experimental research to refinements of more or less empiric formulas we thereby set a limit to our final knowledge. Of course this work had to come first. Such work as that of Mr. Fuller cannot be too highly commended. Are we not now prepared to go somewhat deeper?

E. F. W. Alexanderson: Mr. Fuller has, as already stated, brought the art of radio engineering very close to the electrical engineer by his paper presented tonight. The matter of the transmission of radio messages has become simply a matter of transmission of alternating current. The formulas for calculating the efficiency of transmission have been given, and what is more important, these formulas have been explored throughout a wide range of practical experience.

If a system for radio transmission is to be designed in view of the knowledge we have now, we will need to determine the frequency or eventually the range of frequency that is most favorable, the power necessary and the voltage for which the aerial must be designed. For instance, if we consult the formula given more generally, we find that in some particular cases it can be figured out that a certain rate of transmission requires 100 amperes in aerial. If we assume to use, as suggested here as a typical example, 0.01 microfarad capacity, we find immediately that 100 amperes flowing through a certain aerial will raise the potential of the overhead wires 30,000 volts in the case of 50,000 cycles, or 60,000 volts in case the frequency is 25,000 cycles. An installation for radio frequency is quite a different matter from such frequencies as electrical engineers ordinarily deal with. The losses from corona are extraordinarily high, and while such corona losses would not be considered to amount to anything ordinarily, they may absorb almost all the energy which is available. Insulators, also, may absorb a great deal of power, and therefore as a whole a condition is easily found where the voltage may be excessive, and consequently the lower limit of frequency may, under certain conditions, be determined by the feasibility of the insulation and the maximum voltage.

If we then further examine the data given on the variations that occur due to refractions and other weather phenomena, it is apparent that a certain range of frequency is much more favorable. It appears from these curves, as if under the conditions the frequency should at least correspond to something lower than 6000 meters, in other words, lower than 50,000 cycles. It will be very valuable for the design of apparatus for radio frequencies if some practical rule can be given for the range of frequency that is most efficient, in addition to the general formula and theoretical considerations.

The curves given in the paper suggest that possibly for distances of over 2000 miles we might say that the frequencies should range between 15,000 and 25,000 cycles. If that is so, a basis would exist for the design of alternators for generating that power. I must ask indulgence if my mind runs into the channel of alternator designs and what bearing that may have on the problem.

We are just now testing in Schenectady an alternator for long-distance work, which was designed for 50 kw. at 50,000 cycles, and it is particularly gratifying, in view of the information we have tonight, to be able to state that the alternator has proven to give a good deal more than 50 kilowatts throughout the whole range of frequency from 25,000 to 50,000 cycles. The importance of varying the frequencies in order to accommodate the apparatus to the weather conditions prevailing has already been brought out sufficiently by other speakers as well as in the paper.

I want to explain how this particular alternator can be used for varying frequency. The alternator has a speed range from 1800 to 3600 rev. per min., and for these corresponding frequencies no other tuning is needed than the tuning of the antenna itself. The capacity that the alternator needs for bringing out this power in the antenna and the tuning device, is the regular loading coil. Therefore, if the antenna is tuned for any one frequency, it is only necessary to speed up the alternator until it automatically falls in synchronism with the antenna, and then the load is applied by the power flowing from the alternator and the speed is prevented from getting any higher. Test has shown that the speed under these conditions is stable enough for heterodyne receiving. For accurate work additional refinements of speed regulation are, however, needed.

Returning to the question of the frequencies which are really desirable for radio communication, it is, of course, premature to speak about standardization, but the designer must have some definite idea in mind in order to advance the art at all, and the paper presented tonight has brought us a good deal further forward in the knowledge we really need.

G. H. Clark: These days, the formula in connection with wireless seems to have just about as much immunity from attack as the average patent connected with wireless does, and this formula of Dr. Austin's seems to fare pretty badly in this respect. In order to show that even in the field of spark telegraphy there was wide divergence between the absolute results and the results when calculated by the Austin formula, a test may be referred to which has already been mentioned in Mr. Hepburn's communication. In this test two spark transmitters of widely different efficiencies were coupled to the same antenna and were so adjusted that the same radiations were obtained in each case. On measuring the decrement from the two transmitters it was found that one gave practically twice the damping of the other. The received current was measured, and it was found that the received current was practically twice as great in the case of the transmitter having the smaller damping. There is a case where, according to the Austin formula, it would seem there would be no difference between the two. The conditions were the same, the distance was the same, and yet the decrement had a marked effect in determining the receiving energy. Therefore, that experiment is in line with the wide divergence between the conditions as derived from Austin's formula and the result obtained in connection with Poulsen's experiments.

There is another test I would call attention to, which was carried on recently by the U. S. Navy Department at the stations at Tuckerton and Arlington. The object of the test was to show the results of different wave lengths obtained from a common arc transmitter. The condition in each case was that the power delivered from a 500-volt generator should be a constant. The arc was of the usual type of series arc, directly in the aerial. At various wave lengths the power was adjusted to be exactly the same, and the radiation noted and a curve drawn showing the radiation at different wave lengths. The power was chosen as 30 kw. in each case. It was found in both cases that a very marked maximum was found in the radiation curve. At Tuckerton, where the antenna is of the umbrella type, the natural period of the system was 2500 meters, and the wave length at which the maximum was obtained was 7500 meters, just three times as much. At Arlington, where the antenna is of the flat type, with a natural periodicity of 1900 meters, the best wave length was 5700 meters. It is known that for modern quenched gap transmitters the most efficient wave length for transmission is between 1.75 and 2 times the natural period of the aerial, but in these two cases of arc transmitters it looks as if the best wave length is three times the natural period.

In Mr. Fuller's experiments, he has shown us in his paper that he did not proceed by the method of keeping the energy delivered from the source constant, but, on the other hand, he kept the current in the antenna constant, and in such case it would seem there would be a hump at the transmitting station corresponding to the most effective wave length for that antenna, and it would be only reasonable to expect that the same maximum would be shown in the receiving signals. Almost all the curves Mr. Fuller shows from Honolulu to San Francisco show maxima at 7000 meters, and the object of all these remarks I have made is nothing more than to ask Mr. Fuller if the natural period of the aerial at Honolulu is not one-third of 7000, or 2300.

L. F. Fuller: Mr. Clark's deductions in regard to the natural period of the Honolulu aerial are quite correct; it is approximately 2300 meters.

Referring to his description of the experiments with two damped wave transmitters, of widely different decrements, it is interesting to note that Dr. Austin's latest published damped wave absorption formula includes a correction factor for the decrements at both transmitter and receiver. The earlier formula did not do so, and I presume it is to this Mr. Clark refers.

Dr. Goldsmith has mentioned the complicated theory of operation of the rotary tikker used in these measurements. This complication may, I think, be seriously considered in connection with the fundamental point raised by Dr. Zenneck (in regard to formula (7) of my paper) that we should expect to find telephone current proportional to the received current itself. Prior to the beginning of these experiments, this point, being fundamental, was thoroughly investigated with the result that, contrary to what might be expected theoretically, the telephone current, with the type of rotary tikker used, is proportional to the received watts. This may be explained at present only by the peculiarities of tikker electrical characteristics.

We have had many theoretical formulas covering radio transmission and but two empirical ones, namely—that of Austin for the damped wave, now corrected for decrements, and that proposed in this paper for continuous waves. I agree heartily with Dr. Zenneck that these empirical formulas can only be compared, even in a general way, over a one-thousand meter range of wave lengths, since the Austin data do not go above four thousand meters, and our continuous wave data have not been taken below three thousand meters, and further, since the Austin experiments were over the Atlantic, and the continuous wave data were taken over the Pacific many months later, under widely different conditions.

As men familiar with the making of radio measurements realize, the difficulties encountered in taking data of this character are severe, and it will require years of experimenting before the ultimate formulas with proper constants and factors are determined.

The best that can be done at present is to compare the many theoretical and two empirical formulas with a full appreciation of the limiting features of each.

Presented at the 308th meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 15, 1915.

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INDUSTRIAL CONTROL IN THE FOUNDRY

BY R. H. McLAIN

ABSTRACT OF PAPER

Most of the control devices which are required in a foundry do not differ very materially in their functions from control devices in other industries. However, they have to encounter an unusual degree of dirt. Proper enclosing cases and the latest types of safety protection are advantageous. The crane requires a special kind of control. The difference between alternating-current control and direct-current control is discussed and it is shown that for most cases, where cranes are properly selected and arranged, there is no need of converting alternating current into direct current to accommodate foundry cranes.

CONTROL apparatus in the foundry plays the same vital part as in other industries in regard to safety to operators, safety to apparatus and speed of production. Indeed, safety to the operator and apparatus is important and profitable, not only for humanitarian reasons, but also as an aid in causing continuity and speed in production. Most of the controllers in foundries present problems which are no different from those in other industries, except possibly that there is more dirt in a foundry than elsewhere. Grinders, mixers, blowers, lifting magnets, etc., are the same in the foundry as elsewhere and really require no separate treatment. A foundry crane, however, is different from other cranes, due to the requirement for a very uniform low value of creeping speed for certain operations. Some new devices have been recently developed which have a peculiar relation to the foundry, such as electric welding, electric furnaces, etc. It is the object of this paper to deal briefly with those types of control which resemble closely the control in other industries and to deal more fully with the theoretical side of crane control.

Miscellaneous machines, such as blowers, grinders, mixers, dryers, conveyers, etc., require good substantial hand or automatic starters, capable of starting the apparatus a few times a day. The reliability of these controllers and the safety are greatly enhanced by enclosing them and thus protecting workmen from live parts, and also the controller from dirt. Figs. 1 and 2 show simple hand and automatic starters provided with enclosing covers. Figs. 3, 4 and 5 show a recent development which has been brought about by the great attention which is now being given to safety. These illustrations show a totally enclosed self-starter with line switch, fuses and two contactors for automatic starting. The contactors are controlled by a push-button station. The cover is so interlocked with the line switch that it cannot be opened at the bottom unless the line switch is open. The line switch cannot be closed unless the cover is closed. As shown in Fig. 3, the cover can be locked so that an unauthorized person cannot tamper with the fuses or other parts of the controller. As shown in Fig. 4, the cover can be locked in an open position so that the switch must remain open and no power can be applied to the motor. This idea of enclosing all exposed live parts and providing maximum protection to workmen is gaining in popular favor every day, and I believe all controllers which are near workmen, especially those on cranes, where the operator is always close to the controller, should be thoroughly covered.

Lifting magnets are very valuable in many of the larger foundries where large quantities of scrap or pig-iron have to be handled. As is the case with so many other devices, it seems that the control is the key to the situation here. In large magnets it is difficult and dangerous to disrupt the exciting current suddenly because the long induced arc burns up the controller parts, and the high induced voltage will ultimately destroy the insulation of the magnet winding. To overcome these objections, a discharge rheostat is connected to the solenoids before the exciting circuit is interrupted. Of course, the discharge rheostat causes the magnet to be very slow about losing its magnetism, and consequently in releasing its load. Controllers are provided with a spring-return reverse point which gives, through preventive resistance, a partial reverse exciting current, so as to hasten the release of the load. Reverse excitation need not be used except where it is advantageous to gain time by so doing.

The controlling devices used for arc welding equipments and electric furnaces are usually combinations of hand and automatic control and are comparatively simple.

Arc Welding. The standard arc-welding generator delivers power at from 60 to 75 volts, and the amount of current used

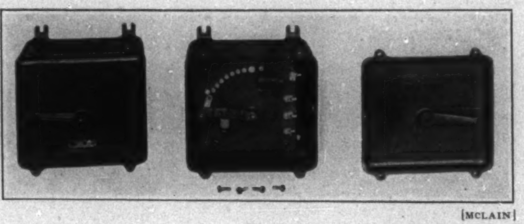

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FIG. 1—COMPLETELY ENCLOSED HAND STARTER FOR DIRECT-CURRENT MOTORS

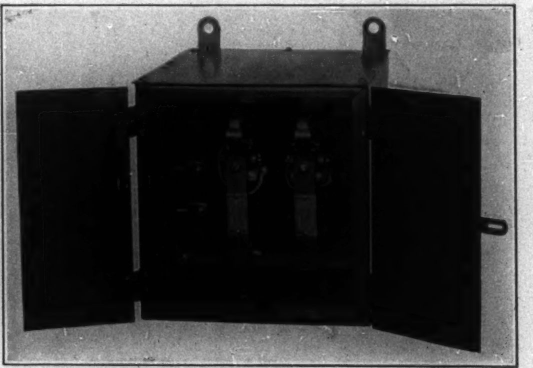

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FIG. 2—THREE-POINT AUTOMATIC STARTER WITH SHEET IRON ENCLOSING CASE FOR DIRECT-CURRENT MOTORS

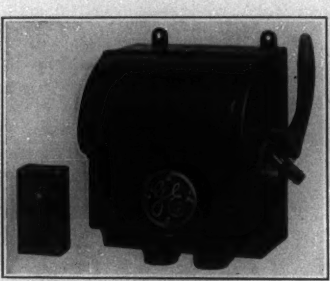

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FIG. 3—TWO-POINT CONTACTOR PANEL FOR SMALL DIRECT-CURRENT MOTORS PROVIDING SAFETY PROTECTION TO OPERATOR

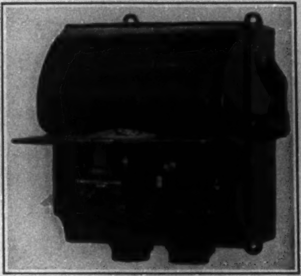

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FIG. 4—TWO-POINT CONTACTOR PANEL FOR SMALL DIRECT-CURRENT MOTORS PROVIDING SAFETY PROTECTION TO OPERATOR

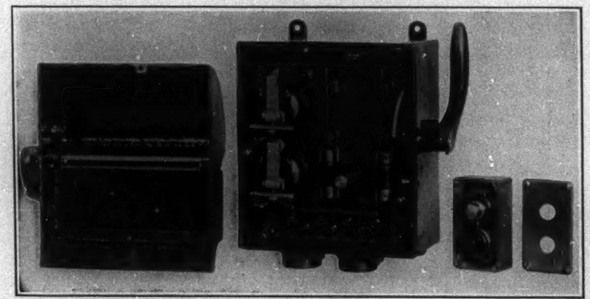

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FIG. 5—TWO-POINT CONTACTOR PANEL FOR SMALL DIRECT-CURRENT MOTORS PROVIDING SAFETY PROTECTION TO OPERATOR

is varied by a rheostat in series with the arc. In small capacities a dial switch is used and in large capacities knife blade switches give better results.

In order to protect the generator against overloads and make it unnecessary for the operator to leave his work to close circuit breakers, an automatic protection is given by a series relay controlling a shunt contactor that normally short-circuits a preventive resistance. When too much current is taken, the preventive resistance is connected in series with the arc and the operator is prevented from injuring the generator and disturbing other operators.

Arc Furnaces. The use of arc furnaces in refining steel requires a constant power control, which is obtained by a balanced current relay controlling contactors for starting, stopping and reversing the electrode motors. This control has advantages over devices formerly used, especially in comparative freedom from opening the main oil switch. A double-throw switch is connected in the control circuit whereby the control can be operated by hand on starting the furnace, and thrown over to automatic control as soon as the furnace reaches normal operating conditions.

Electric Resistance Furnaces. In electric resistance furnaces, operating at lower temperature, such as are required for various kinds of heat treatments and melting nonferrous metals and alloys, a constant temperature control is used. This is accomplished by varying the voltage impressed on the furnace by taking advantage of the characteristics of the resistor, which in this type of furnace decreases in resistance as the temperature increases, and vice versa.

By manipulating a simple relay the contactors are arranged to connect the resistor to a low voltage when the current has increased to a certain point, and to a high voltage when the current has decreased in a similar way. The operation of this control equipment has been very successful, the chart obtained from a recording pyrometer giving practically a straight line.

CRANE CONTROL

The crane is the most important, as well as the most expensive, electrically-operated machine in a foundry, and consequently, a very careful, scientific study of the requirements should be made before selecting cranes. The distribution of heavy and light cranes over the floor should be made to suit the work. A very good solution of this problem in a large foundry is to have large overhead cranes and small sidewall traveling cranes, which serve as feeders to the large ones and which can pass under them.

Maximum full-load hook speed, for which the motor is geared, is of vital importance. A careful analysis of the amount of work to be done and the delicacy of the operations should be made, and the proper speed determined from this. It is clearly evident that a locomotive, geared to run at 60 miles per hour, would not pull uniformly or slowly enough when drawing a thin pattern from the sand, and furthermore this high speed would be of no advantage in increasing the output of the foundry. The temptation is always to make the speed as great as possible, but there are certain definite limits beyond which it is not advisable to go. Forty feet per minute is a speed which has met with very general favor on five-ton cranes, and even 60 feet per minute is in use in at least one merchant foundry where every conceivable kind of work is done. Fifteen feet per minute is quite common on larger cranes. The only trouble on cranes geared for the higher speeds, is that at times a uniform creeping speed of some low value, around one to five feet per minute, must be obtained for drawing patterns, etc. With direct current it is not so hard to obtain this creeping speed, whereas with alternating current it is very hard unless the crane is geared for a lower speed than the direct-current crane. In either case, a well-built crane, a good system of mechanical brakes and such other things, make a decided difference in the accuracy of control. However, with all other conditions equal, alternating current is at a disadvantage.

I know of a case where a crane was designed to take care of only one kind of work, and when this crane was first proposed, 40 feet per minute was, as a matter of course, chosen for the proper maximum hook speed. The crane was to be used for drawing very thin patterns and was to be driven by alternating-current motors. An investigation of the exact cycle of operation of the crane showed that a hook speed of 12 ft. per min. would do just as much work in a day as would 40 ft. per min. With this lower hook speed, alternating current was ideal in operation. Indeed, there are few cases where it is necessary to change the form of power from alternating current to direct current merely to accommodate foundry cranes, provided the crane itself is built properly, fitted with the proper mechanical load brakes and the maximum full-load hook speed is of the correct value.

On a crane running at 60 ft. per min., or less, a controller, viewed from the standpoint of the operator, really needs only two points for hoisting and two points for lowering. The first point should give a uniform creeping speed regardless of the load, and would be used for performing delicate operations. The second point on the controller should give maximum speed, and would be used for making quick trips in transferring the material. Of course in ordinary commercial controllers more than two points of control are necessary in order to transfer the motor speed, without undue shock, from the creeping speed to the maximum speed and vice versa; and there is no objection, from an operating standpoint, to having several such points of control. To obtain this desired form of control in a hoisting direction, a simple rheostatic controller can be used, because the torque on the motor depends directly on the amount of hook load, and the speed can be controlled simply by inserting resistance in series with the armature, or into the secondary circuits of a wound-rotor induction motor, thereby cutting down the speed to the desired point. However, for lowering loads, the tendency is for the load to make the motor run away, and it is necessary either to use dynamic braking control or to equip the crane with some form of a "mechanical load brake." This "mechanical load brake" is an automatic friction braking device which not only holds back against the falling hook load, but also requires power from the motor to drive it in a downward direction; consequently, in so far as the motor is concerned, the work and method of control for lowering is very much like the conditions when the hook is being hoisted, except that the torque required from the motor is practically constant regardless of the amount of load on the hook, whereas in hoisting, the torque depends directly upon the hook load.

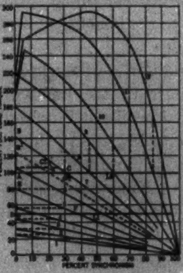

FIG. 6—SPEED-TORQUE CURVES OF WOUND-ROTOR INDUCTION MOTOR WHEN CONTROLLED BY 12-POINT RHEOSTATIC CONTROLLER

Fig. 6 shows the speed-torque curves of a wound-rotor induction motor on the various points of a 12-point rheostatic controller, arranged for foundry service. The object to be attained in laying out such a controller is to provide rheostats of sufficient value and also a sufficient number of controller points, so that as low a value of creeping speed can be obtained as is desirable or necessary for whatever range of torque values the motor will encounter. This particular controller is so arranged that for any value of torque between 18 per cent and 200 per cent, a point can be found on the controller which will give a speed of about 25 per cent or less. By using a larger number of controller points, the value of creeping speed could be kept still lower. In fact, from a strictly theoretical standpoint, by using an infinite number of points, any desired creeping speed of a uniform value could be obtained. However, under practical conditions, there are certain limitations to the benefit which could be thus obtained.

The slip of a motor for a given torque varies on each of these controller points inversely as the square of the line voltage, and this element alone upsets theoretical results. Furthermore, when the gearing of a crane is revolving at low speed, the torque required on the motor is not absolutely uniform but varies sometimes with a slight eccentricity of some part, or as the gear teeth mesh in and out. The resistance elements change in value with temperature. Furthermore, there is always considerably more torque required in order to break static friction when starting the load than is later required to hoist it. All of these variable quantities tend to produce a non-uniform creeping speed on this form of motor; consequently for an operator to maintain a uniform—or practically uniform—creeping speed, it is necessary for him to be continually passing the controller from one point to another. Under such conditions, the advantage to be obtained in having a very large number of points disappears, and it becomes more important that a controller be provided whose design is so substantial and positive that the controller itself does not introduce any more variables into the system than already exist. The resistance material should be made ample in quantity so as not to change its ohmic resistance appreciably due to temperature; and the controller handle should be so made that its movement is relatively large in proportion to the amount of change in motor speed which it produces.

With a controller arranged as is shown in Fig. 6, and provided with large travel of handle and substantial type of resistance, it is easily possible to handle, on a well-designed crane, any kind of foundry work for maximum hook speeds up to something like 40 to 60 ft. per min. However, a great deal of care would be required from an operator to obtain the desired uniformity of speed control when trying to maintain a speed of around 10 per cent. On account of this, it is not advisable to use such a high maximum hook speed where a large percentage of the time is spent in maintaining such a creeping speed. In a large number of merchant foundries there is, of course, only a rare necessity for having extremely low speeds and at all other times the high maximum speed is of great advantage.

I have made a few calculations which show, in definite figures, how quickly an operator is required to turn his controller from one point to another in order to keep the speed down to a low value.

Assume a load requiring 100 per cent torque from the motor for hoisting, but, as is usually the case, assume that 25 per cent extra torque is required to break static friction. It will, therefore, be necessary to turn the controller to point seven, Fig. 6, before the motor will start. The motor will accelerate to 30 per cent of normal speed if the controller is left on this point. The area *A B C* represents the value of torque available for accelerating. If we assume that 100 per cent of the motor torque would be required to accelerate the load, crane and motor parts to full speed in one second, we have the following speed-time curve:

5 per cent speed in 0.128 second
10 " " " 0.284 "
15 " " " 0.484 "
20 " " " 0.774 "
25 " " " 1.224 "

Since it is an easy matter for a trained operator to act in less than 0.2 second, the operator will have ample time to turn back to point 6 before the speed reaches more than 7½ per cent. The hook would then proceed at a uniform speed of 5 per cent on point 6. The above statements, of course, presuppose absolute uniformity of supply voltage and frequency, also uniform torque requirements from the motor.

In order to compare operation with an infinite number of points as against a definite number of points, I have drawn in the dotted line between point 6 and point 7 (6½). This represents the speed-torque curve which gives exactly the correct value of torque to start the load, viz., 125 per cent. On such a point, we would have the following speed-time curve:

5 per cent speed in 0.218 second
10 " " " 0.514 "
15 " " " 1.014 "

It will be seen that on this point the motor would attain a uniform speed of 20 per cent unless the controller were turned back to a position corresponding to point 6, and it is, therefore, evident that there is no particular advantage in having an infinite number of points unless perhaps it gives the operator a little bit more time in which to act. However, unless such a controller is so constructed that the travel of the handle, corresponding to a change from one torque curve to the other, is large, such an advantage immediately disappears. Since the total travel of the controller handle is necessarily limited to that which is convenient for an operator's hand, the limit to the advantage of adding to the number of controller points is quickly reached.

A third speed-time curve has been calculated for a condition of load that requires 50 per cent of the motor torque. Under this condition, with a static friction requiring 62½ per cent to start, point 5 would have to be used and the speed-time curve would be as follows:

5 per cent speed in 0.18 second
10 " " " 0.39 "
15 " " " 0.64 "
20 " " " 0.95 "
25 " " " 1.37 "
30 " " " 1.99 "

It will be seen that the operator will have ample time to turn back to point 4 before a speed exceeding 7½ per cent is reached. In this case he would have to jog along between points 3 and 4 in order to maintain a speed less than 7½ per cent. As stated in the paragraph above, all of these calculations presuppose that several factors remain constant, whereas in fact these factors do not remain constant, and for this reason a great deal of skill and attention is required of an operator in order to maintain a speed as low even as 10 per cent.

When a direct-current, series-wound motor is used, speed-torque curves as shown in Fig. 7 can be obtained by rheostatic control in exactly the same manner as is shown for alternating current in Fig. 6. A typical case would be represented by a controller which would provide curves, point 1, point 2, point 3, point 4 and point 5, and with such a controller the same difficulty in maintaining a creeping speed would be encountered as with alternating current—that is to say, such a controller would begin to introduce some difficulties in operation when used for a maximum hook speed greater than about 15 ft. per min. However, if instead of point 1 we arrange for point *A* by connecting some resistance in parallel with the armature and some resistance in series with the armature and field, then it is a very simple and easy matter to obtain the desired creeping speed. In Fig. 7, point *A* is obtained by arranging the resistance so that at standstill 170 per cent of normal current flows from the line through the series field, and of this current, 136 per cent of the normal current flows through the armature; whereas when the motor is running with no torque at all, the voltage across its armature will be held down to 27 per cent of normal voltage by means of the shunted resistance across the armature. Curve point *A* shows that with a load requiring 100 per cent torque from the motor for hoisting and not over 137½ per cent torque to break static friction, a creeping speed of 7 per cent of normal speed can be obtained. On 50 per cent load, a creeping speed of 16 per cent can be obtained. If necessary, another curve lower in value than point *A* can be provided. This curve shows clearly two marked advantages for the direct current over the alternating current. First, a lower value of creeping speed can be obtained, and second, no especial skill or attention is required of the operator in order to obtain it. The controller is simply turned to the first point and left there without further attention.

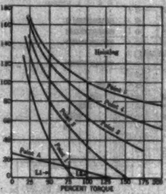

FIG. 7—SPEED-TORQUE CURVES OF DIRECT-CURRENT, SERIES-WOUND MOTOR WHEN CONTROLLED BY FOUNDRY-TYPE CONTROLLER—HOISTING SIDE

As mentioned in the first part of this paper, it is required for lowering either that a mechanical load brake be provided or that dynamic braking be used. Of course on an alternating-current motor it is possible to obtain regenerative braking—that is, when the motor is driven above synchronous speed it acts as a generator and retards the driving load. Such a motor, equipped with a substantial solenoid brake, would give desired maximum speed control of the crane, but would not give desired creeping speed control. With direct current it is possible to connect the motor for lowering so that any desired speed can be obtained uniformly. Fig. 9 shows the connections of a controller arranged to give dynamic braking for lowering. Points 1, 2, 3, 4 and 5 in Fig. 7 show the speed-torque curves on points 1, 2, 3, 4, and 5 of the hoisting side of this controller. Points 1, 2, 3, 4, 5 and 6 in Fig. 8 represent the speed-torque curves on points 1 to 6 respectively on the lowering side of this controller. These latter curves show that when torque is required of the motor to drive the load downward each point of the controller will give a certain amount of torque; whereas should torque be required to hold back a falling load, this same point on the controller will give this required torque at a slightly higher speed. Consequently there is no danger of the load running away on any point.

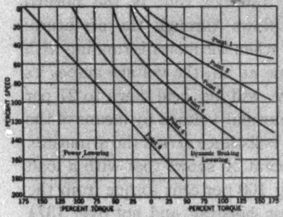

FIG. 8—SPEED-TORQUE CURVES OF DIRECT-CURRENT SERIES-WOUND MOTOR WHEN CONTROLLED BY FOUNDRY-TYPE CONTROLLER—LOWERING SIDE

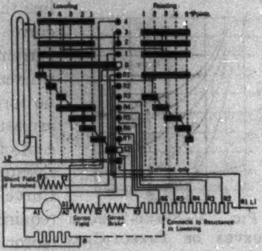
Lowering
6 5 4 3 2 1
Hoisting
1 2 3 4 5 Points
4
3
2
1
B
R1
R2
R3
R4
R5
R6
R7
S2
L2
Terminal only
Shunt Field if furnished
A1
A2
S1
S2
Series Field
Series Brake
R7
R6
R5
R4
R3
R2
R1 L1
Connects to Resistance in Lowering
B

FIG. 9—CONNECTIONS OF CRANE HOIST CONTROLLER WITH DYNAMIC BRAKING ON THE LOWERING SIDE

Reviewing the above paragraphs, I would conclude by saying that for foundry service a careful arrangement of cranes should be made to accommodate the work in the best possible manner. The maximum hook speeds for the cranes should be chosen carefully and scientifically. For maximum hook speeds of 15 ft. per min. and less, ordinary rheostatic controllers are practically always suitable without very special precautions being taken to adapt them for foundry service. For maximum hook speeds above 15 ft. per min., it is sometimes necessary to go to special arrangements. On direct current, a convenient method is to use a shunting resistance across the armature for obtaining creeping speed. For alternating current, it is necessary to provide a larger number of controller points and sufficient resistance to reduce the torque at starting to about 25 per cent of normal torque. While it is true that direct current gives a nicer and more convenient control for creeping speeds, alternating current provides good enough control for practically all cases. Where a foundry is large enough to admit the use of several different cranes, each having a different value of maximum hook speed, the shortcomings of alternating current disappear altogether in most cases. Even where only one or two varieties of cranes are used in a foundry alternating current may give entire success, provided most of the creeping speed work requires not less than 25 per cent of normal speed and only a small portion of the creeping speed work requires as low as 10 per cent of normal speed. The success of this latter arrangement depends largely on the excellence of the mechanical load brake, solenoid brakes and gearing which are furnished with the crane. Where alternating-current power is supplied by a power company, it is, therefore, rarely necessary to go to the extra expense of converting this power into direct current so as to accommodate foundry cranes.

As a basis of recommendation I would present, for the consideration of those present, the statement that alternating current is acceptable when used with a well-built crane, a good solenoid brake and a good mechanical load brake under either of the following conditions:

First: (a) When not less than 25 per cent of maximum geared speed is required for delicate operations.

(b) When torque to break static friction does not exceed running torque by more than 33 per cent; or

Second: (a) When not less than 10 per cent of maximum geared speed is required for delicate operations.

(b) When torque required to break static friction does not exceed running torque by more than 25 per cent.

(c) When the time used up in performing delicate operations does not occupy more than 5 per cent of the total time of the operator.

I hope that the above statements will bring forth enough discussion to settle on rules which can serve as a guide.

DISCUSSION ON "INDUSTRIAL CONTROL IN THE FOUNDRY" (MCLAIN), PITTSBURGH, PA., APRIL 15, 1915.

H. S. Newlin: In the following discussion it is not my intention to describe any one foundry, but to generalize my remarks, portraying as nearly as possible what I consider the ideal foundry control from the standpoint of operation and maintenance.

In the selection of electrical controllers for the foundry, two important factors should be considered: First, safety to the employee; second, maintenance, with its direct effect on production and cost.

In no other line of the metal arts is the simplicity and safety of the equipment so important. The average foundry employee has but the remotest conception of the power which he controls. It is only when, through carelessness or the faulty operation of one of the old style starting rheostats, he is severely burned and the equipment damaged, resulting in foundry delays, that he is brought to realize the dangerous features of the equipment which he operates.

We are all conversant with the ordinary foundry conditions, the dust-laden atmosphere, which fouls the contacts and bearings, and the general carelessness. The controlling element must therefore be as fool-proof as possible, with the removal of the human element as far as possible. This is obtained by means of the magnetic switch, with the push-button station at the operator's elbow, but the switches at a safe distance, properly protected from the atmosphere, yet readily accessible for inspection and repair. This type of control is possible on every stationary unit of equipment, whether alternating or direct current, continuous or intermittent service.

The operator will readily familiarize himself with its simplicity, and its initial cost is soon saved by power conserved in idle periods.

The lifting magnet has proved one of the most essential labor-saving devices about the foundry, yet the installation of a magnet means nothing if the proper controlling elements are not correctly designed and of liberal proportions to receive the kick from the induced voltage upon the release of the current.

The cranes of the foundry influence the production to a great extent; heavy cranes are suitable for certain foundries, while in others the light speedy cranes are adaptable. The type suitable should be carefully decided by the engineer, with the class of work and theoretical tonnage in view. One slow crane can limit a shop's production more than can be imagined. While the a-c. motor is an ideal one for crane operation, this type has not been accepted as standard equipment in the steel mills and until its adoption I do not think it will be introduced into the foundry.

The practise of today is to utilize the jib crane with pneumatic hoists for all the floor work, such as drawing patterns and handling flasks and molds to and from the molding machine, with the large speedy cranes to handle spotting of molds, pouring heats, taking out and transferring castings.

Crane operators, as a rule, are anxious to serve your floors in the best possible manner, but unfortunately they at times overtax their cranes by sudden reversals and plugging stops. There are two ways to govern this:

First, by the installation of complete magnetic control panels, using the master controller; second, using the manual controller in conjunction with current lockout for preventing heavy loads being thrown upon the motor.

Either type is acceptable, although when installing new cranes, I believe that the additional expenditure for the magnetic controller is a capital investment and will return large dividends in decreased repair costs and longevity of motors and equipment.

Limit switches with complete protective panels reset from the cage should be provided. However, the crane presents one of the most striking examples of abuse of any unit of equipment in the foundry and requires the most careful analysis for its economical operation.

Dynamic braking is becoming general on all types of d-c. cranes and its purpose and dependability are familiar to all. I will state, however, that accurate lowering speeds, essential in closing large molds, have become possible only through this method of lowering.

Automatic control of the power house equipment has also worked out advantageously—the pumping of service water, the fire protection system, the varied speeds of stokers regulated by steam pressure, and the control of the motor-driven air compressors, are instances of practical applications of this method.

In summing up the entire situation, I would advocate the installation in all instances of the magnetic control system; although the initial investment is higher, the lower cost of maintenance and element of safety will readily cover the additional expenditure.

T. E. Tynes: I thoroughly agree with the gentleman who has just preceded me in regard to equipping cranes with automatic control. We are doing it just as fast as we can, and our experience shows that it is a wise thing to do, not only from the standpoint of safety but from the consideration of maintenance cost. With d-c. control you can get almost anything you want now in the way of dynamic braking, both creeping speeds or fast speeds, and absolute protection from plugging and severe strains due to careless operation.

Max Hartenheim: Although the author has very completely dealt with the speed control, he has not considered the solution of the question, where the crane has to be run under widely varying loads at a very wide range of speed, if alternating current only is available. The solution is the installation of a variable-voltage control on the crane. It has been adopted in European practice. In America, as far as I remember, it is in use at the Panama Canal. For large cranes in foundries, ship-building yards, etc., where very exact speed regulation under difficult conditions must be obtained, the variable-voltage control gives the best means to that end. As the speed of the motor-generator set can be very high, the price of the electrical equipment will not be so much higher. The complicated connections and large rheostats for three-phase motors are done away with, while on the other hand a good and simple regenerative control for dynamic breaking can be obtained. In some cases it will be useful to compare this solution with that proposed by the author, as the increased first costs might be well counterbalanced by the additional advantages, especially for the creeping speeds.

Brent Wiley: There is one point I did not see mentioned in the paper, to which I think it would be well to give more attention, and that is the question of the control of the trolley motor. In foundry service some of the cranes are used for very rapid work; in fact, I do not know of any service where a crane gets harder work than it does when it is used for handling materials on the floor of a foundry. As a rule, the trolley is geared high, and while it is operated by a small motor that has, perhaps, better inherent protective features than the larger types of motors, there is nothing in service in a foundry that is abused more than the trolley motor. We have reviewed tests which have been made on 220-volt motors of 7.5-h.p. capacity, normal amperes about 30, on service of this nature and found that the plugging load would often be as high as 120 to 130 amperes. This condition, undoubtedly, could be improved materially by the proper application of a magnetic controller and would not only increase the speed of a crane by adding to its working capacity, but would also give very material protection to the mechanical features as well as to the motor.

This point is given more consideration in the larger apparatus, such as ore bridges, where it is, of course, a more important factor, and it has been found in a number of cases that the machine could really do more work when the gear reduction was increased, actually reducing the normal speed of the trolley. This shows that with the small reduction, the acceleration was being accomplished at too high a rate to be as effective as possible. I think that present troubles could be reduced and more work accomplished if this point were remedied in many existing cranes where at the present time the motors are very severely overloaded and abused.

James Farrington: In regard to manual control versus the magnetic control, I differ from one or two of the gentlemen who have spoken. I have found very good results with manually operated controllers, where the motors are small, especially if the crane is subjected to outdoor conditions, where you must protect your automatic controller. In the use of dynamic braking, as you all know, there is one weak feature, namely, in the armature circuit opening up; and if the operator should fail either to throw the controller off or pull out the switch, the load will drop. I have overcome that by using a series switch, that is, operated in series with the armature circuit, when current is above zero. If the armature circuit opens up, the series contactor is deenergized and falls open. This opens the series field circuit in which the solenoid is connected, allowing the electric brake to set. If the operator becomes excited and fails to throw off his controller, it will automatically stop the load. We had occasion to go into that because an operator became excited, and failed to throw off his controller, and we lost an armature by his action. To eliminate the trolley wire trouble we have used iron bars; that is common usage. We have eliminated the common returns, another factor of safety. A good many of the small crane manufacturers still continue to send out a crane with a common return; therefore, if you have trouble on one of the trolley wires, it is manifest on several of them.

S. C. Coey: It is rather interesting to note how much of the apparatus used in the foundry is in general use throughout the plant. Mr. McLain made some mention of lifting magnets and of the troubles which develop in them. I might say in connection with lifting magnets that with any of the modern magnets today we find we have less trouble than with any other type of electrical apparatus. The greatest amount of trouble is, as has been noted, in the controller, and the control of lifting magnets is a problem that is not very easy of solution. I know that some years ago I thought I could build a controller myself that would be considerably better than those in the market, and I built a large face plate controller and it lasted an hour and a half before burning up.

In the matter of arc welding, I believe there is one point overlooked quite generally, and that is the effect of the ultra-violet and infra-red rays from the electric arc on the eyes of the operator. Only yesterday I had a representative of one of the small sheet mills come down to see me, regarding arc welding. He was the man who actually did the work. I was questioning him about the type of glass they used in the hood, and he told me he had obtained a blue glass in town and was using that in the hood; but that he did get some headache even with the use of this glass. Now, this is rather a general experience, and one that cannot be dwelt on too strongly. In our own concern, we went through the same phases of development. We had a blue glass on our arc welders, and the men who operated the welders always complained of headaches, and would lay off every couple of weeks for a day or so. We knew that the effect of ultra-violet rays, at the temperature of the electric arc (6400 deg. fahr.), was greater than anything we had around the steel plant, but we did not appreciate that the effect was so much greater that it would decrease the efficiency of our operators. It was not until our medical examiner was installed and he had kept a record of these various points, that we were brought to a realization of what it meant to eliminate the ultra-violet and the infra-red rays from the electric arc light. There are a number of glasses put out by the optical companies now that we believe will accomplish this purpose, but we are not absolutely sure. For that reason, this is one of the places where it is vitally important that the company should install a system of inspection and medical examination of the men to see just how that eye strain is affecting the operators on the arc welding machines.

Another thing in electric arc work that has been done, and is still being done, I suppose, is the use of 220 volts for arc welding work. In plants having a 220-volt d-c. system, water or grid resistance is often used on the 220-volt circuit for arc welding. It is practically impossible to draw an arc, either a carbon arc or steel pencil and keep it up to 30 or 40 volts, unless 65 to 70 volts is the operating voltage. With a 220-volt power line the operator at times gets the arc greater, and increases the voltage across the arc. The effect of this is to burn the material, and in a number of places where they have tried this type of arc welding, the whole application has been condemned, simply because the welds made were being burned. I know of two plants where arc welding has been absolutely condemned, and on the final analysis that was the whole cause for the condemnation.

I have been asked at what current values we were running arc machines. On very light work we run as low as 75 amperes on the secondary circuit at about 65 volts. For ordinary welding work we are running at 150 amperes at 65 volts, and for some very heavy building-up work, we are running at about 400 amperes.

In crane control for foundry service, the matter of alternating versus direct current has been brought up. In the bridge and trolley it is practically possible to get as good results with a-c. control as can be obtained with d-c. control; but in the hoist control I believe the factors which favor direct current make it advisable to use it, if possible. On divided power and dynamic braking control for hoist motors on cranes, d-c. hoisting gives a flexibility that it is impossible to obtain with alternating current.

The greatest factor, in my estimation, from our experience along this line, is the mechanical brake. At the present time we have over one hundred cranes equipped with controllers that have the same fundamental electrical characteristic as that shown in Fig. 7 of this paper. Before that time most of these cranes were equipped with a mechanical brake, and we found on investigation that over half of our troubles in the cranes were directly traceable to the mechanical brake. We have replaced the mechanical braking equipment with a divided power and dynamic braking hoist control, using two series brakes. In order to overcome the unsafe point of this control which has been pointed out by Mr. Farrington, we have always installed, and are installing double trolley circuits on the armature circuit of the hoisting motor.

Mr. Farrington made the point that he had put a series relay in the armature circuit of the hoisting motor to break the circuit in case there is an opening of this circuit. I really cannot see how that will overcome all the possibilities for trouble there. Suppose we have a circuit such as is shown in Fig. 7 of the paper. If a series relay is put in the armature circuit, after the current divides at the middle point, one circuit going through the series field, series brakes and resistance, and the other circuit through the armature and external resistance, at that point with overhauling load, there will be just sufficient power to drive the load and the current in the armature will drop to zero. Then the current in the armature circuit will reverse and the motor will act as a generator.

The point I bring up is that if the series relay is in the armature circuit when the point of zero current is reached, the relay drops out and throws the circuit breaker out. If it is in the field circuit, then you can have an open circuit in the armature circuit, and will still have the divided power circuit through the brake coils, through the series coils and through the resistance to the other side of the line; and the series relay is not a protection.

Personally, I have come to the conclusion that the only protection against this type of accident is to install in all crane cages, notices that in case of the load starting to run away the controller must be brought to the off point, and it is right there where we have to educate our employees. We can protect the apparatus to a certain point, but after that point is reached, in order to secure safety, we must have a man in the cage who will be able to do something to prevent an accident, if one should be impending.

Now, in any type of crane control, if you have dynamic braking, using a-c. control, with a motor-generator set to give you the direct current for dynamic braking, and the power goes off, you have the same condition. If you have a mechanically braked crane, and the shaft of the mechanical brake should break, then the operator has to go to the off position, or his load will run away and he will cause an accident. I do not see how we can get protection on dynamic braking hoist control by any relay which will absolutely protect against an opening of the armature circuit.

There is one other protective feature we are using at present and find very satisfactory, and that is on the over-travel in the hoisting crane. We use this on foundry cranes and all other cranes in the plant. In the equipment that we are using—and the same type of equipment in its electrical characteristics is now being manufactured by two different companies—the limit switch disconnects the motor from the line, reverses the armature leads with respect to the field leads, and then brings armature and fields in a closed circuit with resistance. The necessity of reversing the field leads with respect to the armature is simply due to the fact that unless they are reversed, the tendency at the armature to generate current will reverse the current in the field, and the residual magnetization in the field, instead of being built up, will be immediately killed, and no dynamic braking effect results. Hence it is necessary to reverse the leads, in order to build up the residual magnetization and get dynamic braking power.

Francis J. Burd: Considerable thought has been given this problem of preventing the load dropping, in case the armature circuit is opened. I agree with Mr. Coey that it is difficult to obtain this protection with the series switch. The best arrangement I have heard of is the use of a mechanical governor on the hoisting motor, and connecting the contacts of the governor in series with a shunt switch, to break the line circuit, cutting power off in that way to set the brake.

In regard to crane control, especially as applied to a-c. motors, it would seem from Mr. McLain's paper that a number of control points are essential; therefore it would appear that a face plate type control is more adaptable for a-c. crane motors than the drum type, because more points are afforded on the face plate than the drum type. Of course, the face plate type has the objection of being open, with its live parts exposed to the operator and dust which is always present in foundries.

With reference to Mr. Coey's remarks on safe limits for cranes, he mentioned two types, with one of which I am very familiar. This type operates in the manner described by Mr. Coey; that is, when the limit stop is tripped by the crane hook, the line power is disconnected and the armature circuit reversed and connected across the series field in series with a resistance. With the stop in this position, it is still possible to lower the hook at a low speed by turning the controller in the down direction. It would seem that safety limits on cranes should be arranged to give absolute protection, in view of the possibility of dropping the hook and load on workmen. I believe it is today carried out along the lines suggested by Mr. Rushmore, in that we do try to educate the operator toward safety as far as possible, in addition to providing safety features in the crane control system. I would offer the suggestion that the crane limit stops be arranged in such a manner that after they are tripped the operator would be put to some inconvenience to reset them, or arranged in such a manner that the crane could not be operated again until a competent person from the electrical department could reset them. This would have the effect of keeping the crane men alive to the job, in that they would either be put to inconvenience or they would be open to censure, if they did not handle the apparatus properly.

C. W. Bartlett: We have developed an electric resistance furnace, and in the bulk of the work the object has been threefold: To obtain a device which will give us absolute control of the temperature in the working chambers; second, a heating chamber which will give us a reducing atmosphere, so as to eliminate the losses of oxidation and scaling; and third, to make the furnace as efficient as possible. A principle of the design is to construct the furnace in general appearance so that it closely resembles the ordinary oil-fired furnace, and line it with a substance which has a negative temperature coefficient, so that when we apply current to the furnace at first it is at a higher voltage than we use when operating at the normal temperature. Of course, as the temperature rises, more current flows, and if we left the voltage constant the temperature would attain a value which would cause the lining of the furnace to burn out. We provide with the furnace a transformer having sets of taps on the secondary side of the winding (for example, 100-50 volts, 90-45 volts, 60-30 volts) and a panel upon which there are mounted two contactors and current limit relays. It is obvious that when the current builds up to a predetermined value, which corresponds to a certain temperature in the heating chamber, the overload current relay drops one contactor and throws over a high-voltage tap to a low-voltage tap across the furnace. The temperature tends to lower slightly. The moment it is lowered to the point where the temperature in the furnace is decreased a very few degrees, the unloaded current relay operates, and throws the higher voltage back across the furnace. So the operation is continually throwing from a volt to a volt and a half across the terminal of the furnace, the furnace itself acting as a huge thermostat. The object of having several sets of taps is to permit adjustment for voltage constant at 1000 deg. cent., or 800 deg. cent., or in fact any temperature value from about 600 or 700 deg. cent., down to 500 deg. cent.

The life of the furnace is much greater than the corresponding oil furnace, because you do away entirely with the blast of the oil flame or gas flame, the heat being a slow, penetrating, radiating heat.

Another result is accomplished by this method of heating. We put a billet in the oil furnace, which we want to raise to 1200 deg. cent., and this tremendous blast of heat is applied to the outside of the metal. Now, the temperature of that flame or the heating element, may be considerably higher than the temperature to which you wish to raise the material. Therefore, the outside of the material may come to the temperature at which you want to work it, but the interior of the material is not so hot and therefore in forging, if you are using it for that work, the metal will not flow uniformly. With the electric heat, you do not get in your furnace a temperature above the point to which you wish to heat your material, and therefore you can let the billet stay in the furnace indefinitely. The interior of it becomes just as hot as the outside; in other words, the outside does not become overheated, does not burn. This gives a billet heated uniformly, so when it is put under the hammer it flows the way the workman wants it to flow. The furnace is especially well adapted for annealing work and for tempering work, and we are experimenting now with a furnace for brass melting work.

D. B. Rushmore: The chief point involved in this subject of control, which has been mentioned a number of times, is how far you can rely on human nature and how far you can prevent a man from doing the work. As Mr. Herbert Spencer says, "Always assume things are going wrong," and work from that point of view.

I was talking with a hoisting man employed by a large mining company, and he told me that some time ago when he was hoisting, his impression at one time was that the skid was down at the bottom of the shaft. He looked at his index and saw it was at the top. He dropped the handles at once, because he knew he had reached the point of mental exhaustion, and knew it was dangerous for him to go on. That is one of the many points to decide—how much to leave to the operator, and how much to automatic features.

J. S. O'Donovan: I will ask a question regarding the use of the electric resistance furnace for tempering. I have had some experience along the lines of tempering, and as this subject has been touched on, I ask if there is any one who knows of a way to temper high-speed steel successfully in an electric furnace. You might say—"Why, yes, we can," but in the pipe business a peculiar condition exists. We make dies, and retemper them frequently. After you have tempered the dies perhaps three or four times, you find the steel has lost most of its original hardness. For instance, we will start out with a temperature of probably 2600 deg. fahr. Later on, after tempering probably six or seven times with the same steel, you find that you have to run the temperature so high that you will blister and spoil the steel to get the proper temperature for hardening. I ask the question: Is it possible in electrical furnaces to overcome that chemical action, which must take place in the high-speed steel, to overcome that tendency of denaturizing the steel to the extent of not being able to get sufficient temper at ordinary temperatures?

C. W. Bartlett: I think that is more a question of chemistry than it is of electricity. I can only say this—I believe there have been some forms of electric furnaces of the bath type for tempering high-speed steel. It has been claimed at times that the bath had a chemical reaction upon the steel and absorbed certain parts which are in its composition. I am not prepared to say that is so or is not so. I will only add that in the electric furnace work, we are now making an equipment which we will use expressly for experimenting in tempering high-speed steel. A few months later we will be prepared to say more about this matter than we are at the present time.

James Farrington: I would like to take issue on the point Mr. Coey brought up about the series contactor on the dynamic brake. If you use an auxiliary holding-in coil, that switch will stay closed to zero current; but in many cases the current will not fall below 10 amperes. Should the desired lowering speed produce zero current in the armature circuit, then you may decrease the speed just a little, not enough to be noticeable, but enough to eliminate that critical zero current. I think you will find it will work.

Palmer Collins (by letter): Mr. R. H. McLain gives a description of the controller for small motors which provides for safety most thoroughly; however, I should think that it would be a much better controller if it were not made to be inoperative when the cover is open. If this cover were locked and opened only by authorized persons, it would be possible to observe its operation. As it is designed at present, in case of trouble, it seems to me from the description that it would be impossible to operate it and see what was going on inside.

C. D. Gilpin (by letter): I have been much interested in Mr. McLain's analysis of the operation of a-c. cranes at low speeds, and I have worked out a typical case based on step 6½, Fig. 6.

Assuming a load of 10,000 lb., a speed of 40 ft. per min. and an efficiency of 80 per cent, the normal load on the motor would be 15 h.p. The equivalent weight at 1 ft. radius of the rotor might possibly vary anywhere from 25 lb. to 65 lb., depending upon the design of the motor and the factor of safety which might be allowed as to size. Assuming this value at 50 lb. and the full load speed at 690 rev. per min., the equivalent rotor weight at rope speed $= 50 \times 0.8 \times (2\pi\, 690)^2 \div 40^2 = 470{,}000$ lb.

Assuming the equivalent weight of gearing is 10,000 lb., the total equivalent weight at rope speed $= 470{,}000 + 10{,}000 + 10{,}000 = 490{,}000$ lb.

Fifteen h.p. is equivalent to 10,000 lb. pull at the rope; therefore, if T = motor torque in per cent of torque at 15 h.p., and F = force at rope, then $F = 10{,}000 \div 100 \times T = 100\,T$. (1) Also, acceleration $= A = F_a\, g \div W = F_a\, 32.2 \div 490{,}000 = F_a \div 15{,}200$. (2)

If starting torque = 125 per cent of torque at 15 h.p., the average acceleration torque $= T_a = (125 - 100) \div 2 = 12.5$ per cent. $F_a = 100 \times 12.5 = 1250$.

Average acceleration $= 1250 \div 15{,}200 = 0.082$. [See (2)].

The normal speed for this controller point $= 0.20 \times 40 \div 60 = 0.13$ ft. per sec. The time to accelerate to 0.13 ft. per sec. $= 0.13 \div 0.082 = 1.6$ seconds.

If it is desired to notch the controller back by the time the speed reaches 10 per cent of normal, the average acceleration torque will be

$$\left(25 + \frac{20 - 10}{20} \times 25\right)\frac{1}{2} = 18.8 \text{ per cent of full load torque.}$$

$$F_a = 1880. \qquad A = 1880 \div 15{,}200 = 0.124.$$

Since the speed $= 0.10 \times 40 \div 60 = 0.067$ ft. per sec., the time to accelerate will be

$$0.067 \div 0.124 = 0.54 \text{ second.}$$

Even with a rotor having half the weight of that assumed in this case, it would appear that Mr. McLain's figures are on the safe side. His figures are based on the excess of the friction of rest over that of motion, and ignore inertia, whereas I have ignored the friction of rest and worked from inertia only. The true condition, of course, lies somewhere between these two assumptions.

The writer would be interested to know if Mr. McLain has made any experiments hoisting at low speeds with one leg of the rotor circuit open.

R. H. McLain: In regard to Mr. Newlin's remarks and the remarks made by several other gentlemen, I will say it is not the purpose of this paper to establish the fact that alternating current should not be used at all, or should be used altogether. I think it is a well-recognized fact that direct current can do all of this work, but the point is, it is advisable to know for economic reasons just how far you can go with alternating current. I always made the assumption that we had a good mechanical load brake. I have not gone quite far enough with that. I should say that the severity of the service often determines whether any mechanical load brake which has been so far made can actually do the work. When you come to most severe service on lowering, there is no question but dynamic braking is the only thing which will stand up.

As to whether alternating current actually has been used or not, I know of numerous installations where it has been used with success, but none of these on really severe work, so much so as to wear out the mechanical load brake too rapidly.

Mr. Newlin also brought up the question of magnetic control. I heartily agree with all that has been said—magnetic control is the thing to be used in all cases, and the only thing that limits the use of it is the expense; but we should use it as far as we can afford to pay for it. Of course, there are certain small foundries handling small material where it is hardly worth while to put in a magnetic control—the magnetic control would be larger than the crane, but the Pittsburgh steel mill district has none of those cranes.

In regard to the variable-voltage control for this class of work, it certainly gives ideal results, and in general the only reason it is not used at present is that it costs more than any other form of control, both for first cost, and also for power consumption. The motor-generator set would be running light all the time. Even the busiest cranes in steel mills are surprising as to the very small amount of power they consume. The small motor-generator set going continuously will consume more power.

I was very glad to hear Mr. Farrington come forward with a suggestion as to over-speed protection. Personally, I think that a good many forms of relays can be used to give this protection, but I am rather inclined to agree with Mr. Burd that the only absolute protection would be some mechanical device. A device does not have to be absolute, to be practicable, because something else might break; but to get absolute protection I think some mechanical device would be better than any other form. It would, of course, involve complications in the wiring.

In regard to the number of points Mr. Burd spoke of, on the controller, that particular controller was of the drum type. Of course, the same number of points could be given on any other type. There were several other questions raised about certain points which I will answer at the same time.

In regard to the failure of the controller causing the load to drop, one gentleman mentioned the advisability of having the operator always turn his controller to the off position in case anything happened. There are a good many controllers—two trolley controllers, one bridge, and two hoisting motor controllers—and for an operator to know just which handle to turn to the off position as something is happening, might tax his thinking powers at that particular moment. I think a better thing to do is to have an emergency control circuit panel convenient to the operator, installed right along with the master controller. The instructions should be that in case anything happens the operator is to strike the handle of this panel and disconnect the main line circuit. A suitable emergency panel consists of a double-throw switch on the back of a slate board, with an insulated knob running through the board. It is smooth, easy to see and hit, and by its use there is no danger of a shock. When it opens, the entire crane is disconnected from the line. That is easier than to turn a controller to the off position, and has the advantage that there is only one knob to think of in case of danger.

Regarding Mr. Palmer Collins's criticism of the controller shown in Figs. 3, 4 and 5, I would say that this is a case where "you cannot have your cake and eat it too". This controller cannot be operated when the cover is open unless the person dealing with the controller knows enough about such a device to short-circuit such of the essential parts of the controller as will render it operative. By so doing it can be operated with the cover open. However, it is not necessary to open the cover in order to make adjustments of the controller, and it is preferable in making repairs to take it to the shop, where it will be easier to disassemble it and correct any faults. It is fair to make the assumption that anyone who knows enough about the controller to make it operate when the cover is open, will know enough to protect himself while making adjustments or repairs on the controller, and to this extent it is not only fool-proof, but safe.

Regarding Mr. Gilpin's discussion, the speed-time curves in the body of my paper were calculated just as Mr. Gilpin's calculations were made. However, instead of assuming specific values of $W R^2$ for the parts as he did, I assumed that the equivalent weights of all of the moving parts of the hoist, motor, etc., were of such value as to require 100 per cent full-load motor torque during one second in order to accelerate the total mass to full speed. I am glad that Mr. Gilpin added this discussion, because, while I had this in mind when writing my paper, I did not bring out the calculations in detail.

Referring to Mr. Gilpin's question as to the low-speed control of an induction motor when operating with one of its rotor windings open-circuited, I would say that speed-torque curves practically similar to points one, two, three and four in Fig. 6, can be obtained by single-phase operation. The total ohms which have to be inserted in the rotor circuit in order to obtain a desired starting torque are something like one-third of the total ohms that would have to be used to get the same reduced starting torque under three-phase operation. If speed-torque curves which give initial starting torque as high as five, six, seven, etc., are attempted with single-phase operation, these curves become distinctly distorted and have a tendency to lock the motor at 50 per cent of synchronous speed. The single-phase rotor is very satisfactory for obtaining reduced torque at starting for values of torque less than about 50 per cent of the rated torque of the motor. This method of control, however, is liable to give rotor insulation trouble on large motors if they are not especially designed for the condition.

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MILL CONTROLLERS

BY H. F. STRATTON

ABSTRACT OF PAPER

Electric power is largely supplanting all other types of power for steel mill work, probably on account of its superior controllability. In almost any type of mill control the object is to start, stop and reverse the machine and its load in the shortest space of time, work done at constant speed being of minor importance. This leads to an investigation of the acceleration of motor-driven machines. The ratio of gearing between the motor and the machine is one of the important factors influencing the time of starting and stopping the machines. Analysis is made of the effect of gear ratio between motor and machine, and equations are deduced from which can be calculated the best ratio of gearing for quick starting, quick stopping, or quick starting and stopping. While these equations may be used to determine theoretical limitations of speed and acceleration, any deductions drawn from their use must necessarily be modified by practical considerations.

I PROPOSE to eliminate from discussion in this paper, controllers for: First, motors driving main rolls; second, motors on cranes or ore bridges, and third, motors operating skip hoists. This confines the subject to that class of controllers somewhat vaguely, but rather understandingly, designated as mill controllers. This caption will be taken to include controllers for the operation of hot metal mixers, charging machines, open-hearth furnace doors, soaking pit covers, ingot buggies, mill tables of all descriptions, screw-downs, manipulators, shears, saws, furnace pushers, cooling beds, etc.

In the business of making steel there has never been a disposition to permit any unproved theoretical considerations to loom very large in comparison with proved practical operating methods. Any proposed system or method has been compelled quickly to establish its just claim to recognition or else promptly be discarded. So far is this statement meant from being a criticism, that I wish to say that I thoroughly believe the present practise in regard to mill controllers represents, to a high degree, a successful compromise between theory and practise, insofar as theory and practise may be considered conflicting.

In a recent paper before the Association of Iron and Steel Electrical Engineers, Mr. Tschentscher said, "The hearty coöperation of manufacturer and user has resulted in the production of reliable electrical equipment, both for generation and utilization. Operation costs of such equipment are far below that of any other type of equipment. Moreover, quality of output and the quantity of the same has been greatly improved by the application of electricity in the iron and steel industry. Lastly, electrical equipment is now so arranged that the resulting installations tend to the promotion of the greatest comfort and safety to the working force, requiring a minimum tax upon its vitality. Electrical engineers in the iron and steel industry may well, therefore, look into the future for a larger demand upon their capabilities and for the development of their initiative and capacity to the utmost." In almost all writing purporting to deal in a comprehensive way with the manufacture of steel, one will find that electric drive is freely conceded as being a very important and probably indispensable factor in the rapid development of this industry to its present effective status. The effectiveness of electric power in a steel mill is largely due to the fact that the equipment has been designed and built to meet the special requirements of steel mill work It is significant that the phrase "mill type machinery" means, without further explanation, machinery that will stand up to its work.

In a steel mill, electric power, considered merely as power, is no better than steam power or hydraulic power. Electric power has largely supplanted all other types of power probably because of its superior controllability. One man controls the operations of possibly three or four motors which start, stop, or reverse the ponderous machinery necessary for the manufacture of steel. These operations are performed with comparatively little physical or mental effort, they are duplicated in their most efficient form thousands of times each day, and they are so hedged around with protective devices that the hazard to men and machines has become astonishingly small.

The manufacture of steel is essentially a series process; the continuity of operation of each step hinges on the preceding and succeeding steps being performed regularly and on time; a slowing down of any important part of a mill is equivalent to slowing down the entire mill; the output of a five million dollar unit—and therefore the return on this investment—may be limited by the slowness of the screw-down of the blooming mill.

Of the entire time and work expended in a mill, a part is devoted to actual manipulation of the steel in heating, pouring, rolling, shearing, sawing, and finishing; this part is basic; it is itself the manufacture of steel; it may be improved, it cannot be eliminated. The other part of the work and time is devoted to the adjustment of machinery and conveying the steel from one operation to the next one; it consists, for instance, in the opening and closing of furnace doors and soaking pit covers, the transportation of the product by ingot buggies and tables, the adjustment of screw-downs and gages, the movements of manipulators. Such operations, although necessary, become waste time if they delay the real operations of heating, rolling, shearing, etc. This, in general, is the class of work to which mill controllers are applied. Their general specifications may be summed up by saying that it is taken as a matter of course if they operate satisfactorily day after day, but it is a matter of much comment if they cause a half-hour's delay.

In almost any type of mill controller the main object is to start, stop, or reverse the machine and its load in the quickest feasible period of time. The work done at constant speed is of minor importance. I believe, therefore, that a general investigation and analysis of the acceleration of a motor-driven machine is a proper subject to be considered in this paper.

In the ensuing discussion of the acceleration of a motor and its load, the entire work performed by the motor will be considered to be of only two kinds, viz., the inertia load and the work load. The inertia load will be taken as the number of foot-pounds necessary to make any selected change in the rotary or linear velocities of all bodies moved by the motor, including its own armature; this is exclusive of any work done against friction or in lifting any weights against gravity; it is, in short, what is known as the flywheel load. The work load will be taken as the sum of all the other amounts of work necessary for driving the machine; it will be represented for the most part by the friction of the machinery, but in some machines the lifting of weights against gravity will be a part of the work load.

During the process of acceleration of a motor, the torque developed by the motor is, of course, governed solely by the motor current, the high and low values of which are governed by the controller. When full line voltage has been applied to the motor, the torque is still dependent upon the motor current, but the motor current is now determined, first, during that time in which the motor speed is increasing, by the work load and the inertia load, and second, during the later period of relatively high and constant speed, mainly by the work load.

In other words, in the complete acceleration of a machine driven by a series or compound-wound motor, there are two stages through which motor and machine must pass before they attain a situation of even instantaneous stability.

The first stage begins when the armature and the starting resistance are connected to the supply lines and ends when the starting resistance has been completely short-circuited and the armature is receiving full line voltage. As the great majority of mill controllers are of the magnetic-switch current-limit type, manual controllers will not be considered. The initial current peak is determined and limited by the starting resistance, and is generally approximately 150 per cent of rated full-load motor current. The first and all valley currents are determined and limited by the operation of series current relays or magnetic switches. All following peak currents are determined and limited by the successive sections of resistance permitted to remain in series with the motor. The time and the mode of variation between each peak current and its succeeding valley current, are governed by the relation between developed motor torque and work and inertia loads. With the usual magnetic switch controller peak currents may be assumed roughly to be 150 per cent, and valley currents 100 per cent, of rated full-load motor current. The average shape of the current-time curve between peaks and valleys may be approximated; it curves downward so that the average is somewhat less than half the sum of the peak and valley currents. If the characteristics of the motor are available it is possible to make a fairly accurate determination of the average developed motor torque during this first stage. With any given machine and driving motor, the inertia load is precise and definite; it is the sum of the number of foot-pounds that must be imparted to each rotating element to bring it to its final speed; in each case it is the product of a constant $\frac{2\pi^2}{g}$, the moment of inertia (weight $\times$ square of the radius of gyration), and the square of the number of revolutions per second which is finally attained. The amount of inertia load which is absorbed by any rotating member in attaining any definite speed of rotation is independent of the time but is directly dependent upon the speed attained. The time, however, varies inversely with the driving torque.

Let T = torque tending to rotate a body without friction;
N = final speed of rotation of body;
I = moment of inertia of body;
t = time required to accelerate from rest to speed N;
C = a constant.

Then

$$t = \frac{C\,I\,N}{T}$$

The work load is indefinite and may vary at different speeds. On a mill table, it certainly increases if the bearings are tight, if the grease is cold, or if the rolls are warped by excessive heating.

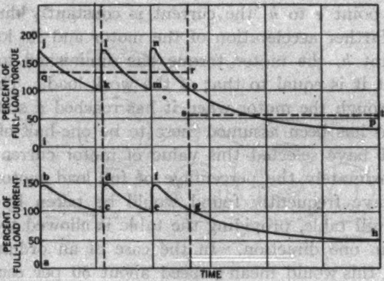

FIG. 1

The second stage begins when full line voltage is applied to the armature, and ends when the developed motor torque equals the torque of the work load. As long as the motor torque is larger than that of the work load, the surplus of motor torque is devoted to a further increase in speed.

Fig. 1 is a graphical representation of the variations in motor current and motor torque as they occur in the acceleration of a motor-driven machine from rest to a speed at which the work load is equal to the developed torque. In the diagram of Fig. 1, the horizontal axis represents time, and the vertical axis represents, in the case of the lower curve, motor current, and in the case of the upper curve, developed motor torque. Considering first the current curve, when the line switch is closed at *a*, the current quickly rises to the peak at *b*, and the motor starts to accelerate, the current dropping until it has reached approximately full load value. The first accelerating switch is supposed to close at *c*, giving the peak *d*, after which the current again drops to full load value as at point *e*. Another accelerating switch is here supposed to close, giving the motor armature full voltage, which results in the peak *f*. The occurrences from the point *a* to the point *f*, collectively, form what has already been called the first stage of acceleration in the motor. It is convenient to extend this stage to the point *g*, which might be described by saying that it is that instant of time when the motor current has dropped to its full load value, and when, therefore, the motor has attained normal full-load rated speed. From the point *g* to *h*, the current is constantly diminishing, due to a further acceleration of the motor and its load, until, at the point *h*, the motor torque has diminished to such an extent that it is equal to that of the work load. The current passing through the motor when it has reached a state of constant speed has been assumed here to be one-half of full load current. I have selected this value of motor current because it is approximately the percentage of full load motor current which I have frequently found would be taken by a motor driving a mill table, providing the table is allowed to run continuously in one direction. In the case of an ordinary series mill motor, this would mean a speed about 50 per cent greater than normal, and while I realize that many motors driving mill tables would attain speeds much higher than this, yet this figure will be representative enough to serve present purposes.

The upper curve *i*, *j*, *k*, *l*, *m*, *n*, *o*, *p*, indicates the variation in motor torque, which, of course, in the case of a series motor, varies at a more rapid rate than the motor current. In other words, when the motor current varies from full load to 50 per cent overload, the motor torque varies from full load to about 75 per cent overload. Correspondingly, when the motor current has dropped to about one-half full load, the motor torque is about one-third full load. The horizontal dash line *q r* is the average motor torque developed during that portion of the acceleration of the motor which begins when the line switch is closed and ends when the motor armature attains normal full load speed with full voltage applied. The horizontal dash line *s t* represents the motor torque developed during the remainder of the acceleration and ending when the speed of the motor has become constant.

Any factor that prominently influences the time of starting and stopping mill machinery is worth investigating. The ratio of gearing between motor and machine is such a factor and is one of decided importance. This has been guessed at ever since motors were used in a mill. On identical machines in different mills—and sometimes in the same mill—this ratio of gearing has varied 10 to 1. In an experience with a good many hundred mill controllers, I have seen more troubles traceable to poorly selected ratios of gearing than to any other single cause.

The rest of this paper will be an attempt to analyze the effect of the ratio of gearing between motor and machine, and to determine what this ratio should be to give the quickest starting and stopping.

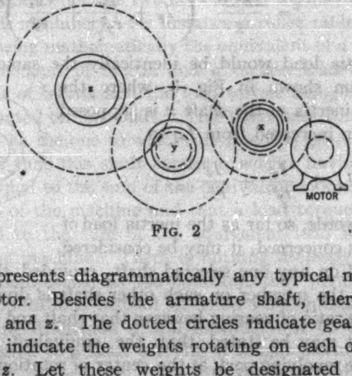

FIG. 2

Fig. 2 represents diagrammatically any typical mill machine and its motor. Besides the armature shaft, there are three shafts x, y, and z. The dotted circles indicate gearing and the solid circles indicate the weights rotating on each of the shafts x, y, and z. Let these weights be designated respectively W_x, W_y and W_z and let their corresponding radii of gyration be called k_x, k_y and k_z. Then their moments of inertia are as follows:

$$I_x = W_x k_x^2$$
$$I_y = W_y k_y^2$$
$$I_z = W_z k_z^2$$

Let r_x = ratio of gearing between shaft x and armature, so that the armature rotates r_x times as fast as shaft x;

r_y = ratio of gearing between shaft y and shaft x; and

r_z = ratio of gearing between shaft z and shaft x.

Then if shaft x is revolving at a speed of S revolutions per second, the speed of shaft $y = \frac{S}{r_y}$, and the speed of shaft $z = \frac{S}{r_z}$.

The inertia load of any rotating member equals $\frac{2\pi^2}{g}$ times its moment of inertia, times the square of its speed. Therefore if the entire system is rotating at such an angular velocity that the speed of the shaft x is S revolutions per second, the inertia load of the shafts x, y and z is as follows:

$$\text{Inertia load} = \frac{2\pi^2}{g} S^2 I_x + \frac{2\pi^2}{g} \cdot \frac{S^2}{r_y^2} I_y + \frac{2\pi^2}{g} \cdot \frac{S^2}{r_z^2} I_z$$

$$= \frac{2\pi^2 S^2}{g} \left(I_x + \frac{I_y}{r_y^2} + \frac{I_z}{r_z^2} \right)$$

This inertia load would be identically the same if we had the condition shown in Fig. 3, where the moment of inertia of the shaft x is supposed to have been increased from I_x, to

$$I_x + \frac{I_y}{r_y^2} + \frac{I_z}{r_z^2}.$$

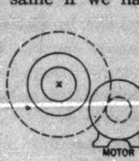

FIG. 3

In other words, so far as the inertia load of a machine is concerned, it may be considered concentrated on any one selected shaft, provided the moment of inertia of the member on each other shaft is divided by the square of the ratio of gearing between that shaft and the selected shaft. Or it may be stated that the equivalent moment of inertia of one revolving part, at the center of rotation of another revolving part to which it is geared, is inversely proportional to the squares of the respective speeds of rotation of the two parts.

Referring back to Fig. 2, assume that on shaft x, there is a load torque of F_x pound-feet; on shaft y, one of F_y pound-feet; and on shaft z, one of F_z pound-feet.

If shaft x makes N revolutions, shaft y makes $\frac{N}{r_y}$ revolutions, and shaft z makes $\frac{N}{r_z}$ revolutions.

Then

$$\text{Work load} = 2\pi N F_x + 2\pi N \frac{F_y}{r_y} + 2\pi N \frac{F_z}{r_z}$$

$$= 2\pi N \left(F_x + \frac{F_y}{r_y} + \frac{F_z}{r_z} \right)$$

It is apparent that the work load would be the same with the conditions of Fig. 3, provided the load torque of shaft x is supposed to have been increased from F_x, to $F_z + \frac{F_y}{r_y} + \frac{F_z}{r_z}$.

In other words, so far as the work load of a machine is concerned, it may be considered concentrated on any one selected shaft, provided the load torque of each shaft is divided by the ratio of gearing between that shaft and the selected shaft.

The significance of these two laws is that we may consider any piece of mill machinery—for instance a roller table or a screw-down—as being mathematically the equivalent of a body having a certain moment of inertia and a certain load torque, both the moment of inertia and the load torque being considered to be concentrated on one shaft. This shaft may conveniently be assumed to be the one to which the motor is geared, and it will be assumed that this shaft carries a weight having a moment of inertia equal to the sum of the equivalent moments of inertia of all parts of the machine and that a load torque acts on this shaft equal to the sum of the equivalent load torques of all parts of the machine. There is nothing uselessly complicated in these assumptions; on the contrary, they permit the use of simple computations instead of some very intricate ones. In the following discussion a mill machine will be considered as a motor geared to a shaft carrying a weight having the equivalent moment of inertia of the entire machine and acted on by the equivalent load torque of the entire machine. In short, we have the conditions shown in Fig. 3.

Let I_1 = moment of inertia of machine
I_2 = moment of inertia of armature
N = number of revolutions to be made by machine
r = ratio of gearing of machine to motor
T = mean torque developed by motor, in pound feet
t = time of acceleration in seconds
F = load torque of machine.

The total work done by motor while the machine makes N revolutions

$$= 2\pi TrN \quad (1)$$

The total work done against the load torque while the machine makes N revolutions

$$= 2\pi FN \quad (2)$$

The average speed of rotation of the machine is $\frac{N}{t}$; hence its final speed of rotation is $\frac{2N}{t}$.

Similarly, the final speed of rotation of the armature is $\frac{2rN.}{t}$

The inertia load of the motor is

$$\frac{8\pi^2 I_2 r^2 N^2}{gt^2} \quad (3)$$

Similarly, the inertia load of the machine is

$$\frac{8\pi^2 I_1 N^2}{gt^2} \quad (4)$$

Now, if the machine starts from rest and makes N revolutions, (1) = (2) + (3) + (4)

$$2\pi TrN = 2\pi FN + \frac{8\pi^2\ N^2}{gt^2}\ (I_1 + I_2\, r^2) \quad (5)$$

From (5), we get

$$t = \sqrt{\frac{4\pi N\ (I_1 + I_2\, r^2)}{g\ (Tr - F)}} \quad (6)$$

Equation (6) then indicates the length of time required to start from rest and move the machine any definite distance corresponding to N revolutions. The following important deductions can be made from equation (6).

A. Since the current is proportional to the motor torque T, the power input is proportional to Tt; in other words, the kilowatt-hours necessary to move the machine any number of revolutions is least when the time, t, is a minimum.

B. On the same basis of reasoning the heating of the motor is least when the time, t, is a minimum.

C. The time of acceleration, t, increases as the square root of the number of revolutions, *i. e.*, $\sqrt{N}$.

D. Increasing the moment of inertia of either the machine or armature, increases the time, t.

E. Increasing the motor torque, T, decreases the time, t.

F. Increasing the load torque F increases the time, t.

G. Tr must always be greater than F, or t will be infinite; in other words, the motor would never accelerate.

The ratio of gearing, r, enters into the equation in a manner not simple enough to permit of the determination of its effect by inspection. To determine what should be the value of r in order that t may be a minimum, the differential of t with respect to r is equated to zero. Omitting the various steps of the calculus, the following equation is obtained:

$$r = \sqrt{\frac{I_1}{I_2} + \left(\frac{F}{T}\right)^2} + \frac{F}{T} \tag{7}$$

By the use of equation (7) and knowing the moments of inertia of machine and armature, the motor torque and the load torque of the machine, that ratio of gearing, r, may easily be determined, which will cause the machine to make N revolutions in the shortest time. It is to be noted as important, that N does not appear in equation (7). In other words, this most favorable value of r as determined by equation (7), is the same, no matter how many revolutions are made by the machine.

The equations (1) to (7), inclusive, relate to the condition of the machine starting from rest and making N revolutions. Of equal importance is the condition that the machine, when running at any speed, should be brought to rest in the shortest time by reversing the current through the armature.

Let I_1, I_2, r, T and F have the same significance as in the case of acceleration of the machine. In addition let

t_1 = time of stopping in seconds.
S = speed of machine in revolutions per second when motor is reversed.

The inertia of the machine

$$= \frac{2\pi^2}{g} I_1 S^2 \tag{8}$$

The inertia of the armature

$$= \frac{2\pi^2}{g} I_2 r^2 S^2 \tag{9}$$

The average speed of the machine in revolutions per second $= \frac{S}{2}$. Therefore, the machine makes $\frac{St_1}{2}$ revolutions before coming to rest. Similarly the armature makes $\frac{Srt_1}{2}$ revolutions before coming to rest.

The total work done by the motor while bringing the machine to rest, from a speed S,

$$= \pi TSrt_1. \tag{10}$$

The work load of the machine assisting the motor in bringing the machine to rest

$$= \pi FSt_1. \tag{11}$$

Then (**8**) + (**9**) = (**10**) + (**11**)

$$\frac{2\pi^2 I_1 S^2}{g} + \frac{2\pi^2 I_2 r^2 S^2}{g} = \pi TSrt_1 + \pi FSt_1 \tag{12}$$

From (**12**) we get

$$t_1 = \frac{2\pi S\ (I_1 + I_2 r^2)}{g\ (Tr + F)} \tag{13}$$

Equation (**13**) indicates the length of time required to bring a machine to rest from a speed S, by reversing the current through the armature. As in the case of acceleration, the following deductions can be made by inspection:

A. The power input in the motor is a minimum when the time of stopping, t_1, is a minimum.

B. The heating of the motor is least when t_1 is a minimum.

C. The time of stopping varies directly as the speed, S, of the machine.

D. Increasing the moment of inertia of either armature or machine, increases the time, t_1.

E. Increasing the motor torque, T, decreases the time, t_1.

F. Increasing the load torque, F, decreases the time, t_1.

As before, the differential of t_1 with respect to r is equated to zero to determine that ratio of gearing, r, which will give the quickest stopping. This value follows:

$$r = \sqrt{\frac{I_1}{I_2} + \left(\frac{F}{T}\right)^2} - \frac{F}{T} \tag{14}$$

Note that this value of r involves the same quantities that enter into equation (**7**) and that it is independent of S.

We have now determined two values of r from equation (**7**) and (**14**). That of equation (**7**) is for quickest starting from rest and making any number of revolutions; that of equation (**14**) is for quickest stopping from any speed of rotation. It would be possible to make another determination to give the value of r for quickest starting plus quickest stopping. It is not possible to say whether quick starting or quick stopping is of the most general importance; also it is not true that a motor is reversed every time it is started. It seems reasonable, therefore, to assume that the most favorable value of r would be the arithmetical mean of the two values as determined by equations (**7**) and (**14**).

This gives the value of the ratio of gearing, r, as follows:

$$r = \sqrt{\frac{I_1}{I_2} + \frac{F^2}{T^2}} \qquad (\mathbf{15})$$

It is next in order to make some practical use of the equations. Assume that it is desired to investigate the ratio of gearing of some motor-driven machine, say a mill table. For any standard mill motor it is easily possible to secure the weight, W, of the armature and its radius of gyration k, k being expressed in feet.

Then $$I_2 = Wk^2 \qquad (\mathbf{16})$$

Preferably adjust the controller to give peak currents of 150 per cent full load and valley currents of 100 per cent full load. The rated full-load current of the motor can be determined from the speed-torque curves of the motor. Connect a recording ammeter in the motor circuit, accelerate the motor from rest and allow the motor to run until the motor current has become constant. From the speed-torque curves of the motor, determine the torque at the motor in pound-feet corresponding to the constant motor current; let this torque be called H.

Then $$F = rH \qquad (\mathbf{17})$$

where r represents the existing gear ratio.

On the record made by the recording ammeter, note accurately the point where the motor has dropped to exactly full-load value after full line voltage has been applied to the motor. In other words, this is the point where the motor current reaches full-load value after the last accelerating switch has closed, and is indicated by g in Fig. 1. Measure accurately on the record the time between the closing of the line switch and the point g. This interval of time is t. From the speed-torque curves of the motor and the current record, determine the average torque developed by the motor during the interval of time beginning when current first passes through the armature, and ending when the motor current drops to full-load value after full line voltage has been applied to the armature. In other words, determine the average torque developed by the motor during the interval of time t. This torque is T and is expressed in pound-feet.

From the speed-torque curves of the motor, determine the speed of the armature at the point g. Let this speed be called P, which should be expressed in revolutions per second. If the armature starts from rest and reaches a speed of P revolutions per second, its average speed during this time of acceleration is $\frac{P}{2}$ revolutions per second. The total number of revolutions made by the armature during the time t, rotating at an average speed of $\frac{P}{2}$ revolutions per second, is obviously $\frac{tP}{2}$.

Therefore

$$N = \frac{tP}{2r} \qquad (18)$$

Equation (**5**) may be solved for I_1 as follows:

$$I_1 = \frac{2.56\ (Tr - F-)\ t^2}{N} - I_2 r^2 \qquad (19)$$

I, r, F, t, N and I_2 are all known, and the moment of inertia of the machine, I_1, can easily be determined by inserting these values in equation (**19**).

Equations (**7**), (**14**) and (**15**) can be solved for r when T, I_2, F and I_1 are known. The determination of T has been explained; I_2, F and I_1 are respectively obtained from equations (**16**), (**17**) and (**19**). If quick starting is of major importance, r can be determined from equation (**7**). If quick stopping is the chief consideration, r should be determined by the use of equation (**14**). On the other hand, if quick starting and quick stopping are of approximately equal importance, equation (**15**) should be used.

A more comprehensive study of the question would be to determine by the use of equations (**6**) and (**13**), different values of t and t_1, corresponding to different assumed values of r, and then to plot curves between r, t, and t_1. These are shown in Fig. 4, where curve A represents different values of t_1 for different values of r and curve B represents different values of t for different values of r. Curve C is obtained by adding the ordinates of curves A and B, and therefore shows, for different values of r, the time of starting plus the time of stopping. Curve A is a minimum on the line aa, curve B on the line cc and curve C on the line bb. For any ordinary piece of mill machinery, the position bb would probably indicate the most favorable value of r.

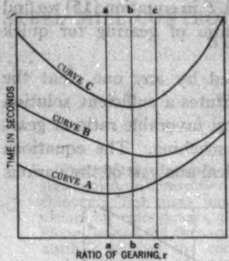

FIG. 4

To illustrate the practical application of these equations, a certain motor-driven mill table will be selected, concerning which I happen to have the necessary data. In Fig. 5 is shown the current-time record, and in Fig. 6 are shown the speed-torque curves of the motor.

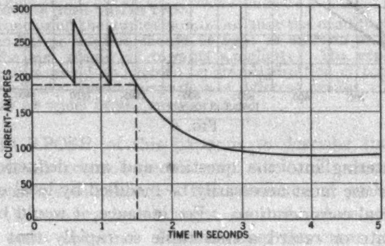

FIG. 5

From Figs. 5 and 6, it is found that

t = 1.5 seconds
T = 630 pound-feet
H = 150 pound-feet
P = 9.5 revolutions per second.

It is known that the weight of the armature is 900 pounds and its radius of gyration is 0.55 ft. Therefore $I_2 = 900 \times 0.55^2 = 272.3$

Since $r = 5$, we have $F = rH = 5 \times 150 = 750$.

From equation (**18**), $N = \frac{tP}{2r} = \frac{1.5 \times 9.5}{2 \times 5} = 1.425$.

Inserting these values in equation (**19**) and solving, we find that $I_1 = 2892$.

By using the values of I_1, I_2, F and T in equation (**15**) we find that $r = 3.46$ would be the best ratio of gearing for quick starting and stopping.

It certainly should not be assumed by any one, that the use of these various equations constitutes a sufficient solution of the problem of determining the most favorable ratio of gearing for any particular motor-driven machine. The equations must be regarded merely as a theoretical analysis of the various factors entering into the question, and any deduction drawn from their use must necessarily be modified by local conditions and practical considerations. For instance, it would be foolish to accelerate or retard a mill table so rapidly that the steel would slip on the rolls or that handy control would be lost. Furthermore, due to variations in friction, the work load may change from day to day or from hour to hour, so that some assumption must be made as to its average value. In short, this is no hair-splitting subject; on the other hand, it is believed that a judicious application of theory to practise will in this case lead to results which will prove to be substantial and worth-while improvements.

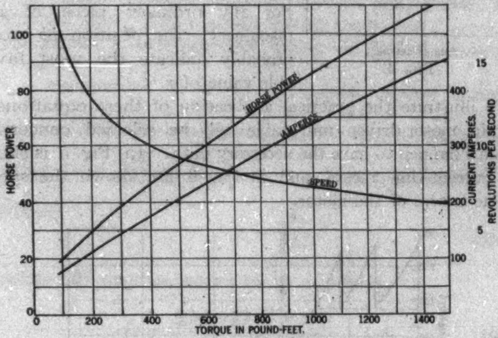

FIG. 6

Presented at the 308th meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 15, 1915.

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STEEL MILL CONTROLLERS FROM THE OPERATOR'S STANDPOINT

BY J. S. RIGGS

Abstract of Paper

The writer discusses control problems from the operator's standpoint, in connection with bloom mill and rolling mill machinery. The most important consideration is that no provision for emergencies can be allowed, and when the ingot or bloom leaves the furnaces for the rolls it must be kept moving until it reaches the cooling beds. Any interruption in this cycle means scrap material and lost time. To fulfill these requirements the equipment must always stand up to the service and be as nearly fool-proof as possible. The full magnetic controller in the writer's opinion meets the above requirements better than any other type.

The requirements of the different classes of machinery are tabulated and from this tabulation it is shown that the control can be standardized in four distinct type, sone or the other of which will meet all conditions of mill equipment: 1. Full reverse single-speed type. 2. Full reverse multi-speed type. 2a. Full reverse multi-speed type with dynamic braking. 3. Non-reverse push-button type.

In conclusion the author points out that the conditions to be met and their solution should be kept as uniform as possible and the aim should be towards simplicity. The expense of duplication would be avoided by standardization of parts, and this would also permit comparison of different makes of apparatus on an equal basis.

THE PURPOSE of this paper is to describe the forms of electrical control peculiar to steel mill service, "from the operator's standpoint." It is possible and probably usual to treat the subject by averages, to make statements as the result of many opinions. In this paper the other general procedure will be followed, in that the ideas are as the writer sees them. This plan has been adhered to purposely. I do not expect complete agreement. I do hope this method will provoke constructive criticism, all to the end of definite recommendation, if such be possible, toward uniformity of attack to meet the given condition.

The steel mill is distinct in many ways from any other manufacturing industry, and one of the most important of these distinctions is that no provision for emergencies can be made; that is, when an ingot, bloom or billet leaves the furnace for the rolls it has to be kept moving until it reaches the cooling beds. Any delay or interruption in this cycle means scrap material and loss of time.

Considering the above service requirements and operating conditions, the equipment must stand up to the service, and be as nearly fool-proof as it can possibly be made. The full magnetic controller, in my opinion, meets the above requirement better than any other type, and also has several additional advantages which may be briefly enumerated as follows:

1. Superior ability to handle heavy currents at a minimum of maintenance cost and delays.

2. Inherent current-limit acceleration feature, taking acceleration entirely away from the operator.

3. Can be operated by a small master controller which is easy to handle, thus eliminating the element of fatigue of operator.

4. Limit switches and automatic cut-out switches can be applied in any position so that "slow-down" dynamic brake stop, as well as any other automatic feature required, can be obtained.

5. Complete remote-control circuit breaker protection at a very slight additional cost.

6. "Safety first"—removes all arcs from immediate vicinity of operators. In fact, with magnetic control, the operator is insulated from all live parts.

In order to bring out clearly the different equipments with their control in, for example, a bloom mill and a rolling mill, the following outline sketches and tables may be of assistance.

The control for the following outlined equipment, which covers practically typical mill equipments, can be standardized in four distinct constructions, as follows:

1. Full reverse, single-speed type.
2. Full reverse, multi-speed type.
2a. Full reverse, multi-speed type, dynamic braking.
3. Non-reverse, push-button type.

(1) The full reverse, single-speed type should contain the following apparatus:

4 Reverse switches, mechanically interlocked.
3 or 4 Accelerating series or lock-out switches.
Three switches up to 75 h.p.; above 75 to 200 h.p., four switches.
1 Main line contactor.

2 Overload double-coil relays.
1 Main line switch, double-pole, single-throw, safety type.
1 Control switch, double-pole, single-throw, and fuses.
1 Terminal board.
1 Angle iron or pipe frame.
1 Resistance, to be mounted on rear of frame below panels.
1 Single-speed master radial arm type with overload reset in off position.

This controller will take care of at least 50 per cent of mill work and can be used on the following equipment:

A. All roller tables.
B. Screw-downs.
C. Rollers on tilting table.
D. Soaking pit covers.

Limits can be used with this control in any place where conditions may require them.

(2) and (2a) The full reverse, multi-speed type should contain the following apparatus:

4 Reverse switches, with mechanical interlocks.
4 or 5 Accelerating switches, shunt type series accelerating relays. Four switches up to 75 h.p.; above 75 to 200 h.p., five switches.
1 Main line contactor.
1 Dynamic brake switch.
2 Overload double-coil relays.
1 Main line knife switch, double-pole, single-throw, safety type.
1 Control switch, double-pole, single-throw, and fuses.
1 Terminal board.
1 Angle iron or pipe frame.
1 Resistance to be mounted on rear of frame below panel.
1 Multi-speed master radial arm type with overload reset in off position.

This type of controller can be used wherever conditions are such that a single-speed equipment, even with the plugging feature, will not meet them. For instance, this type of controller should be used where varying loads obtain, where refinement of control is required, where dynamic braking or slow-down features are desired, and can be used on the following equipment:

A. Kick-off.
B. Dogs or drags on transfer tables, hot-bed, etc.
C. Furnace pushers.
D. Tilting tables.
Hoist-lowering.
E. Hot metal mixers.
F. Open hearth floor type charger, bridge, hoist, trolley and reel.

No.	Equipment Operated.	Type Contr.	Reverse Non-rev	Type Master	Limits	Special Features.
	Bloom Mill.					
1	Soaking Pit Covers.	Magnetic	Full rev	1-Speed.	2-Way.	....
2	Ingot Del. Table.	"	" "	"	....	....
3	Mill Appr. Table.	"	" "	"	....	....
4	Mill Rev. Table.	"	" "	"	....	....
5	Two-High Mill. A-Screw-down.	"	" "	"	....	....
6	Mill Rev. Table.	"	" "	"	....	....
7	Shear Appr. Table.	"	" "	"	....	....
8	Shear.	"	Non-rev	Push button	....	....
9	Shear Del. Table.	"	Full rev	1-speed.	....	....
	A-Kick-off.	"	" "	Multi. "	2-way.	slow down
10	Hot-Bed. A-Drags or Dogs.	"	" "	"	....	"
	Rolling Mill.					
1	Furnace Pusher.	"	" "	"	"	" "
2	Furnace Feed Tables.	"	" "	1-speed.	....	....
3	Furnaces	"	....	....	....	....
4	Furnace Discharge Table	"	" "	1-speed.	....	....
5	Tilting Tables.					
	A-Bridge.	"	" "	Multi "	....	....
	B-Hoist.	"	" "	" "	2-way.	Dyn. brake Lowering
	C-Rollers.	"	" "	1-speed.	....	
6	Three High Rolls.	....	...	....	....	....
7	Tilting Tables. Same as 5.					
8	Hot Saw Appr. Table.	Magnetic	Full rev	1-speed.	....	....
9	Hot-Saw	"	Non-Rev.	Push-button.	....	....
	A-Hot-Saw Feed.	"	Full rev	Multi-spd.	2-way.	Auto. feed depending on cut.
10	Hot-Saw Del. Table.	"	" "	1-speed.	....	....
	A-Hot-Saw kick off.	"	" "	Multi-spd.	2-way.	slow down
11	Hot-Bed.					
	A-Hot-Bed Tipper.	"	" "	" "	"	" "
	B-Hot-Bed Drags.	"	" "	Multi-spd.	"	" "
12	Straightener Appr. Table.	"	" "	1-speed.	....	....
13	Straightener	"	Non. rev.	Push-button	....	Field control. Vibrating field relay.
14	Shear Appr. Table.	Magnetic	Full rev	1-speed.	....	....
15	Shear.	"	Non-Rev.	Push-button	....	....
16	Shear Dis. Table.	"	Full rev	1-speed.	....	....
	A- " " " Kick-off.	"	" "	Multi-spd.	2-way.	slow down
	B-Transfer Dogs	"	" "	" "	"	" "
17	Cold Saw Appr. Table.	"	" "	1-speed.	....	....
18	Cold Saw.	"	Non-rev.	Push-button	....	....
	A-Cold Saw Feed.	"	Full rev	Multi-spd.	2-way.	auto. feed depending on cut.
19	Cold Saw Dis. Table.	"	" "	1-speed.	....	....

This type of control without the dynamic brake feature is also suitable for the following:

G. Tilting furnaces.

H. Tilting table bridge.

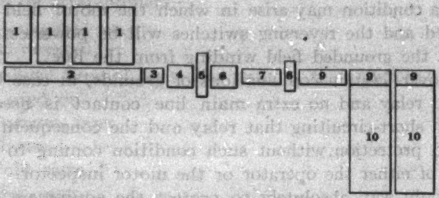

Fig. 1—Bloom Mill

1. Soaking pit
    A. Soaking pit covers
2. Ingot delivery
3. Mill approach table
4. Mill reversing table
5. Two-high mill
    A. Screw-down
6. Same as 4
7. Shear approach table
8. Shear
9. Shear delivery tables
    A. Kick-off
10. Hot-bed
    A. Hot-bed drags

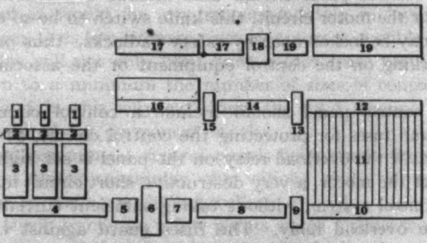

Fig. 2—Rolling Mill

1. Furnace pushers
2. Furnace feed roller tables
3. Furnaces
4. Furnace discharge roll table
5. Tilting table
    A. Bridge
    B. Hoist
    C. Rollers
6. Rolls
7. Same as 5
8. Hot-saw approach table
9. Hot-saw
10. Hot-saw delivery table
    A. Hot-saw delivery table kick-off
11. Hot bed
    A. Hot-bed tipper
    B. Hot-bed drags
12. Straightener approach table
13. Straightener
14. Shear approach table
15. Shear
16. Shear discharge table
    A. Shear discharge table kick-off
17. Cold saw approach table
18. Cold saw
19. Cold saw discharge table

The question may arise as to the extent to which line protection devices shall be employed. A reversing controller in its simplest form does not provide for the disconnecting of the series field of the motor from one side of the line. This is not such an important detail so long as the controller is not provided with overload relays, but if overload relays are installed, and the contactors which are used for reversing the armature and to open and close main line circuit are depended upon to afford line protection in combination with overload relay or relays, a condition may arise in which the motor field will be grounded and the reversing switches will be powerless to disconnect the grounded field winding from the line.

Moreover, certain combinations of grounds, in case but one overload relay and no extra main line contact is used, may result in short-circuiting that relay and the consequent loss of overload protection, without such condition coming to the attention of either the operator or the motor inspector.

The only way absolutely to protect the equipment against short circuits and overloads is to install two relays, one in each side of the line, and also install a contactor in that side of the line which feeds the motor field winding, which arrangement gives the most complete protection possible to obtain.

Each control panel should also include a main line knife switch for the motor circuit, this knife switch to be so equipped that it may be locked open by safety padlocks, thus protecting men working on the control equipment or the associated machinery.

Each control panel should include a control circuit knife switch, and fuses for protecting the control circuit, as it is obvious that if the overload relay on the panel is set high enough to protect the motor, a very destructive short circuit may occur in the control system, without taking sufficient current to trip the main overload relay. The fuses guard against this contingency and make it possible to connect the control circuit outside the main line knife switch, so that whenever the motor inspector desires to test out the control system he may pull the main line knife switch and operate all contactors without running the motor.

(3) The non-reverse, push-button type should include the following apparatus:

1 Main line contactor.
3 or 4 Accelerating switches, series or lock-out type.
  Three switches up to 50 h.p.; four switches from 50 to 200 h.p.
  The last accelerating switch to hold in on zero current.
1 Overload double-coil relay.
1 Main line double-pole, single-throw, knife switch and fuses.
1 Terminal board.

1 Shunt field protecting relay. Not considered necessary below 30 h.p.
1 Angle iron or pipe frame.
1 Resistor mounted on rear of frame.
1 Push-button "start," "stop" and "reset."

Additional to above, where variable speed is required, as for instance on straighteners—

1 Vibrating field relay.
1 Field rheostat.

The above type of controller without the additional features can be used on

A. Furnace fans.
B. Shears.
C. Cold saws.
D. Hot saws.

In fact, this type of controller is suitable for the majority of constant-speed mill equipments.

I have not attempted to give horse powers for any of the equipment mentioned because of the wide range in the power required by mills, due to different size mills and local conditions, but it would be my recommendation in laying out a mill to keep to as few different sizes of motors as possible throughout. This will not only keep down motor spare parts but will cut down to a minimum the number of sizes of controllers required, and in this way cut down the total amount of spare parts required for permanent stock.

I would recommend control panels being made up of an assembly of slates containing the various pieces of apparatus which go to make up the controllers.

I will touch briefly on a few points which I think would help the operator. If there is to be some standardization so that he can compare different makes of apparatus on an equal basis, these items will be of assistance:

(1) Contactors.
    Area of contacts.
    Pressure between contacts.
    Rating per unit area of contact.
(2) Resistors.
    Standard ratings.
    Cross-section.
    Contact area.
    Spacing.
    Type.

Contactor coils should be interchangeable on the same size apparatus of one manufacturer. Use external resistance when coils have to stand continuous service, rather than a special coil.

In conclusion, the aim pointed out in the introduction is emphasized. Make the conditions to be met as uniform as possible. Solve these, both from the manufacturing and the operating standpoints, by uniform methods. Strive for simplicity. Save the expense of duplication. These I believe to be engineering fundamentals peculiar to the subject.

DISCUSSION ON "MILL CONTROLLERS" (STRATTON), AND "STEEL MILL CONTROLLERS FROM THE OPERATOR'S STANDPOINT" (RIGGS), PITTSBURGH, PA., APRIL 15, 1915.

H. F. Stratton: I apologize for appropriating such a big topic as mill controllers, and then discussing only part of one division of it. Nor do I feel that the apology is an empty formality, because I appreciate that other parts of the subject have such a direct bearing on the one discussed that they should be considered at the same time.

Generally when a motor is applied to a machine it is a question of horse power; that is to say, the capacity of the machine as a power translating device must be at least the equivalent of the power demands of the machine. This is the situation which generally exists with motor-driven machine tools or cranes.

In the case, however, of a motor driving a typical piece of mill machinery, the situation is different. It is not a question of horse power, but it is a question of torque. The average mill motor starts, runs, is stopped or reversed, and these operations are repeated hour after hour; the main purpose is to control these short movements with the smallest amount of wasted time. I am quite sure that it would not do to state the requirements any less broadly, because an improvement in one feature might lead to, and in fact be the direct cause of a greater disadvantage in some other part. For instance, it sometimes happens that time is lost in the end if a machine is rotated so rapidly that it becomes correspondingly difficult to stop it accurately. In short, in a situation of this kind there would be lost that very valuable but elusive condition which may be designated as "handy control."

The paper which I have written deals mainly with the question of the relative speeds of the motor and machine, or in other words, with the ratio of gearing between motor and machine. I do not propose to read this paper, but instead to make some comments and offer some compromises which it seems to me are permissible.

Equation (**15**) is an expression which gives the value of the ratio of gearing for quickest starting and quickest stopping of a motor-driven mill machine. The equation involves the moment of inertia of the armature, the moment of inertia of the machine, the load torque of the machine, and the developed motor torque. Since writing the paper I have examined some data which I happen to have, relating to several mill tables and other mill equipment, and I have found that the moment of inertia of the machine is generally at least five or ten times the moment of inertia of the armature. I have also found that the square of the ratio of load torque to motor torque is small compared to the ratio of the moments of inertia, and in the several instances which I examined it averaged about $\frac{1}{5}$ of this value. Now there is not much difference between the square root of a number and the square root of that number increased by $\frac{1}{8}$. In fact the difference is only about 6 per cent. It seems foolish to quibble about 6 per cent when I have already disregarded motor friction and windage and when some very broad assumptions must be made as to the average load torque, and when the developed motor torque will certainly vary as the motor or the resistance becomes hot or as the voltage fluctuates. If, then, you are disposed to accept this compromise, the ratio of gearing would be determined by merely taking the square root of the ratio of the moment of inertia of the machine to that of the armature.

On the basis of this assumption the rest of the investigation is correspondingly simplified, because it now remains to determine only the moment of inertia of the armature and the moment of inertia of the machine.

I assume that if you apply to the motor builder he will cheerfully furnish the moment of inertia of the armature, and you can obtain the moment of inertia of the machine in the following simple manner:

Allow the motor to run until it reaches a constant speed and measure its current and its speed of rotation when at constant speed. From the speed-torque curves of the motor determine the torque corresponding to the motor current. Shut off power and measure accurately the number of seconds required for the machine to stop through the influence of friction. Then the moment of inertia of the machine can be easily computed from these quantities. On this basis the square root of I_2 over I_1 will indicate the ratio of gearing to be used.

This would be theoretically the correct analysis if the machine were frictionless. On the same assumption, if the condition be imposed that the machine shall make any specified number of revolutions, this established ratio of gearing would then mean that the least energy would be stored up in the rotating parts. If the least energy is stored in the rotating parts, then the least energy will have to be taken out of these parts to bring them to rest. This would seem reasonably to point to quick and accurate stopping. Any deductions or arguments relating to quick stopping apply equally well whether that be accomplished by plugging or dynamic braking, since in either case the motor exerts a restraining torque in opposition to the existing direction of rotation.

Very likely there will be a disposition to criticise this theoretical handling of an intensely practical matter, and I fully realize that if the subject is not considered with sympathetic intelligence, the theory is valueless. There of course can be no object in accelerating, for instance, a mill table so rapidly that the steel skids on the rolls, or that its movements are merely a succession of violent jerks. It occurs to me, however, that some approximate determination could be made as to how fast it is advisable to accelerate a given mill table, and that on that basis the most appropriate gear reduction and the most appropriate size of motor might be employed.

A. G. Pierce: I wish to comment on Mr. Riggs's paper. To me it is notable because of its comprehensive treatment of the processes involved, and because of the assertiveness of his conclusions as to the proper type of control for each process. Further, standardization is emphasized. If it is possible for the steel mills to follow standardization to the end of securing general uniformity of panel constructions, even though the latter may not be exactly alike, it will most certainly result, I believe, in cheaper first cost, simplicity in manufacture, saving in upkeep, and simplicity in operation.

David B. Rushmore: The matter of standardization, of which Mr. Pierce speaks, is one of the hopeful movements in this direction of all forces working toward a common end. Just how much ought to be done, and just how far it is possible to standardize apparatus manufactured by different companies, is a question.

The electric motor has always been subservient, it has gone around trying to adapt itself to the other machines, and that is one of the reasons why the manufacturing companies list over 5000 different varieties of induction motors. The public must necessarily pay for this, and think of what that means—five thousand different varieties of capacities, frequencies, voltages, phase types, etc., of one kind of motor.

The electric motor is beginning to ask that the other machine be adapted to it, that instead of adapting the electric motor to all other forms of apparatus, why cannot the steel mill be adapted to it, why cannot we change the rolls, why cannot we change the tables, etc., in order to meet, at least half way, the requirements of electric motors? In some of the largest steel mills which have been electrified, a step has been made in this direction. The designing engineer in the factory never fully grasps what the operating man wants. The operating man never appreciates the difficulty of standardization, of getting out modifications of apparatus, of special developments —he cannot, unless he has been through it.

Glenn E. Stoltz: In Mr. Stratton's remarks he brought up one very interesting thing, a very simple and accurate method of arriving at the flywheel effect of a machine or motor. I think that method can be used to much greater advantage than to try to calculate. He simply gets the friction load of the machine running idle and throws open the line switch and allows it to drift to a stop. If we assume the friction torque is constant, we get a straight-line curve, plotting the speed of the motor against time, provided the torque is constant. That applies approximately to the mill type motor and table, but we cannot use it so well on apparatus which has greater flywheel effect—for instance, a motor-generator set, to which is attached a large flywheel. There is a certain amount of energy which acts similarly to a fan, and we have a greater torque at the high speed. The curve comes down very little at first, and then smooths off to a straight line; and we have no change when the apparatus comes to a rest. Probably within five to ten per cent of the time when it comes to a rest at the end we lose the oil film in the bearings, and naturally that increases the torque considerably and really shortens the time of coming to rest. In apparatus of that type it is better to take the reading every five or ten seconds in getting the speed, plot a curve, take the straight line part of it from the origin, and not follow it clear to dead rest.

Mr. Stratton has discussed a very important issue in the selection of motors for mill tables, screw-down, and similar applications. He has carefully treated the theoretical side of this subject by means of elementary mechanics. However, many of us do not deal so constantly with these terms and no doubt would prefer to attack this problem in a more simplified manner.

As has been pointed out, the load on the motor may be divided into the friction load of the driven machinery, the inertia of the driven machinery, and the inertia of the motor itself.

To arrive at the inertia loads, the fundamental formula E equals $\frac{1}{2}MV^2$ may be used, in which E represents energy expressed in pounds and feet, and M is the mass of body which is equivalent to its weight divided by 32.2, and V is velocity in feet per second of the rotating body at its radius of gyration. This formula then becomes E equals $\frac{W}{64.4} \times V^2$. Dividing this formula by 550 will give the number of horse power-seconds stored in the body at the velocity of V. The load can be expressed in either of these two terms without involving any other items than the weight of the body and peripheral speed at its radius of gyration. In expressing this in horse power-seconds, that is, the stored energy in the body, we have a term which we can comprehend. If we get the horse power-seconds of energy stored in the table and in the motor, we have terms which we understand. We may say the moment of inertia of a body may be 1000, but that does not mean much, if anything, to us. If we express it in thousand horse power-seconds, we know, if we give up 100 horse power in 10 seconds, we have 1000 horse power-seconds.

If the problem involved does not warrant an extremely accurate solution, the radius of gyration of both the motor and rolls, if the latter are hollow with the shaft extending from end to end, may be taken at from 0.7 to 0.8 of the outside radius. It has been found on ordinary armatures that if the total weight includes the shaft, 0.7 is a very close figure; however, if the weight of the shaft is omitted 0.8 should be used

Unfortunately, other conditions enter into the consideration of this subject which overshadow the importance of our theoretical results.

In the first place, the most advantageous speed of the table or machine in question must be definitely determined by the operator, and from tests on similar apparatus the friction load can be assumed. If you have a roll table, it is up to the mill man to know at what speed he desires to operate it. That is a fixed condition which we must accept. If the apparatus to be driven is a mill table which carries metal that is delivered to the roll before the motor attains full speed, the motor should be geared to give a speed somewhat above that specified, so that the actual speed desired will be attained under average operating conditions. Suppose we want a speed of 300 ft. a min. on a table, we would probably gear the motor to give 400 ft. per min.; in other words, the metal will enter into the rolls before the table will reach full speed, and the average speed attained then is 300 ft. a min. When operating the table at constant speed, the motor should run from 20 per cent to 30 per cent above its rated speed, which is equivalent to approximately 60 per cent of its full load capacity. This permits the motor to run light for a period of time and allows the commutator to polish. If the size of the motor is such that it operates at full load or overload when running a table at constant speed, the motor is not given an opportunity to polish its commutator, which reduces its ability to withstand peeks without incurring excessive maintenance.

Very often too large a motor is selected in order to get quick acceleration. Excessive speed on the table does not necessarily mean greater dispatch in handling the material, as the metal may slide. Although the commutator has an opportunity to polish at this excessive speed, the plugging or braking current is very severe when the motor is reversed at the high speed.

After checking a large number of roll table drives, we have found that motors operating at practically full load are brought to rest in approximately 0.3 second; those overloaded and operating at higher speeds very seldom require more than 0.5 second, so that it is not important to give this phase of the subject much weight.

The formula developed by Mr. Stratton does not apply when the table reaches full speed before the metal enters the roll. In railway work it is a well-known fact that the car having a gear ratio that gives best acceleration is soon overtaken by a similar equipment on which the gearing has been selected for both acceleration and a fixed distance at constant speed. We gear a motor to give good conditions in starting and running, and the time of stopping is of such short duration it is of little importance in comparison with starting.

With the formula given above, the inertia of the driven machine and of the motor may be determined. The inertia load of the gearing and countershaft, irrespective of the gear ratio, is of very little importance as its value seldom exceeds five per cent of the total, so we can simply drop it.

Every manufacturer builds a standard line of mill motors, the speeds of which are fixed, so that there is little opportunity to exercise any discretion as to the speed ratio between the motor and the table except in the selection of the number of motors to be applied. It is simply a matter of selecting either, say, 50-h.p. or 75-h.p. motors, and practically all mill motor manufacturers have adopted standard speeds, which are substantially the same.

On such applications as a screw-down, the inertia and fixed load of the driven parts are small in comparison with that of the motor applied. On a drive of this kind it is therefore important to reduce the inertia load of the motor, which is done by placing two in series.

On tables of large inertia and friction load, in comparison with the inertia of the motor, it is better to select either one motor or place two in parallel. In every case, irrespective of the drive, the problem resolves itself into a comparison of the friction and inertia load of the driven machinery and the inertia load of the motor. The remaining items are not of sufficient importance to receive consideration; for instance, the friction of the motor itself. I believe Mr. Stratton designated that as being very small and not worth consideration.

At one of the large mills in Ohio, there is an example of a mill table driven by two motors in series. The inertia of the motors is very small in comparison with the friction and inertia load of the table and the motors are operating at a disadvantage. If they are placed in parallel and gear ratio changed, the current per motor would be reduced to 60 per cent of the present value.

At another mill is a roll table driven by one motor which has a large flywheel effect. When this table is brought up to speed, 54 per cent of the energy is required in the motor itself, 20 per cent in inertia of the rolls, 2 per cent in gear, and 24 per cent in friction. If this motor were replaced by two smaller motors in series, 11 per cent of the energy would be required in the motors themselves, 50 per cent for the roller inertia, 5 per cent in the gears, and 30 per cent for roller friction. This simply effects a more economical distribution of the input to the motor so that more of it is utilized as useful work, resulting in quicker manipulation of the table.

M. A. Whiting: I am inclined to disagree with Mr. Stoltz in his estimate of the value of the results obtained by such a theoretical treatment as Mr. Stratton's. It is true that in many cases we have rather inaccurate data, and there are a number of minor errors in the method itself. After all of these are taken into account, in many cases it will be practicable to make a calculation based on one gear ratio or one set of conditions for the acceleration and complete duty cycle of a given reversing motion, and repeat the calculation with a considerably different gear ratio. A comparison can be made in which it is probable that the errors, while considerable in each computation, will be relatively about the same. We then have a reasonable basis of comparison between the two sets of conditions, from which we are reasonably justified in deciding by example which gear ratio is the better. Having determined by this calculation which would be better, we may in extreme cases be 30 per cent or 40 per cent in error as to the actual results which either one of these arrangements would give, and still have a correct relative idea of the two cases. In many cases the duty can be determined much closer than the 40 per cent mentioned, and the calculations from the result will be considerably closer.

In looking over Mr. Stratton's paper, I find the following statement: "The average speed of rotation of the machine is $\frac{N}{t}$, hence its final speed of rotation is $\frac{2N}{t}$"; in other words, the assumption is made that the rate of acceleration is uniform. The friction is assumed uniform, and the assumption is then that the net accelerating torque is uniform, or is equivalent to a uniform value. The formulas which follow are all based on that assumption, and therefore relate particularly to short moves during which the armature rheostat is being cut out and in which the motor does not run for any appreciable length of time in accelerating to the final speed on its series characteristics.

The formulas, therefore, cover a large number of the cases which arise on reversing mill machinery, but do not cover all of the cases. If the friction is very light compared with the torque developed during the period of cutting out the resistance, the free running speed will of course be very much greater than the speed at which the armature resistance acceleration is completed. In this case a speed-time curve can be computed by taking successive increments, while the motor is accelerating on its series speed characteristic, and computing step by step the increments of time necessary to accelerate from one value of rev. per min. to another value of rev. per min., plotting these in the form of a curve, for example, with the time horizontal and the speed vertical, the area of which represents distance.

It is an easy matter, having plotted such an acceleration curve for a given gear ratio between motor and driven machinery, etc., to lay in the retardation, assuming that the average torque would be uniform during current limit retardation by plugging. In that way the area under the closed curve, bounded at the end by the inclined line representing the retardation, will represent the distance traversed. Comparisons can be made of different speed-time curves for different ratios in order to determine the most advantageous ratio.

In a problem requiring this kind of analysis, it is quite usual to find that the gear ratio which enables us to make the short moves most quickly will not enable us to make the very long moves most quickly. In some cases, therefore, it becomes necessary to compare a number of short moves with a number of long runs, and compare also the importance of saving time in stopping accurately with the importance of making long runs rapidly, arriving at a practical conclusion in that way.

J. A. Albrecht: The speed of reversal of the table rolls is not usually the limiting feature in the operation of the mill. I believe that is a point which has not been given enough attention.

There are certain operations to perform before the ingot goes through the mill. It takes a definite time to handle the ingot, grab it on the lower side of the rolls, guide it to the top side of the rolls, and straighten up the piece for the pass and prepare for the operation of rolling. This manipulation is lost sight of in figuring the time of the roll. The men in the engineering departments are called on to reverse the tables probably twice as fast as the men can handle the steel, and the operating men do not take that point into consideration. While we can satisfactorily reverse the table, it is a greater strain on the motor and table gearing and everything of that sort affects the upkeep of the motor. In regard to the table Mr. Stoltz spoke of, driven by the big motor; he figures a large saving by putting in a smaller motor. We have oscillograms of that mill. It is an old style motor, fifteen years old, with an armature 3 feet in diameter, and the oscillogram shows the time consumed in turning the mill over from full speed in one direction to full speed in another direction was 1¾ seconds. That is entirely too fast, as far as handling the steel is concerned. Consequently that plan is putting twice as much energy into handling the table as is necessary to still make the same time on the mill.

One of our leading mill engineers has always had a theory about keeping one table still, the receiving table. As the approaching table, taking the ingot into the mill, is moved down toward the mill, the receiving table, is still, and the ingot pounces out on to it. As it comes back out of the mill, the operating table, which is now the receiving table is still, and the same operation is repeated, and on paper it looks very fine. The idea is that there is probably a saving of 30 per cent in the energy by not having to plug that table. I have heard some mill men say there is a somewhat excessive wear on the rollers nearest the mill. If any of you gentlemen know anything about reversing blooming mill tables which operate in that way, I would be glad to have some one discuss it and let us know if there is anything in the theory of excessive wear on the roll, as that is the only thing which would limit that method of roll table drive.

E. J. Murphy: As to the results of Mr. Stratton's calculations, I am not prepared to say. The accuracy of the product of a mathematical mill depends on the accuracy of what you put into the hopper. I believe wherever possible, calculations should be made, that is, if there are any data available as a basis of calculation. It will save a great deal of unnecessary work and sometimes rather bad blunders.

We frequently find machines either over-motored or very much under-motored. Where quick reversal is necessary a motor too large for the job will be a serious disadvantage, and there are cases where considerable time could be saved by using small motors. That point has been brought out by other speakers.

In Mr. Riggs's paper, several points attract my notice. He seems to advocate the use of dynamic braking instead of plugging. I do not suppose that means for all applications, and I would like to hear some comments from the operating engineers as to the advisability of using dynamic braking. I should say in cases where they had to make an accurate stop, it might be preferable.

He advocates a shunt field protecting relay. Probably a great many of us have actually had cases of trouble from this shunt field protecting relay dropping out, due to the transformer action of the series field in the case of a compound motor.

Various efforts have been made to devise some scheme to prevent this action. I recently had to solve a problem of that sort. It was quite difficult to obtain any relay that would have a time element that would avoid the back action of the series field. We managed to solve the problem by using what was practically a small contactor with a heavy copper sleeve around the copper. With this particular relay it was actually possible to take off the exciting current and it then took three to five seconds for the contacts to open.

With reference to the matter of the standardization of contactors, Mr. Riggs refers to the area of contacts, pressure between contacts, and rating per unit area of contact. I should think it would be difficult to ascertain the area of the contact, because in many designs of standard contactors the action is a rolling one and the contact is made across what is practically a line. In so far as the standardization of this sort of a device is concerned, I think it depends on the results obtained, as to the life, temperature, and general safety, opening the arc, etc.

The same remark applies to resistors. The design of resistance also has so many variable factors that I do not doubt we could obtain good results by quite different arrangements. Further, where you are using a resistance for accelerating and not continuous duty, the important point is the actual weight of the grids, which determines the heat storage; with infrequent stopping this is more important than the actual continuous capacity.

R. H. McLain: There is just one point in Mr. Riggs's paper that I have noticed with which I disagree. He says: "Contactor coils should be interchangeable on the same size apparatus of one manufacturer." In the next sentence he says, "Use external resistance when the coils have to stand continuous service, rather than a special coil." I am not just sure what he means, but I certainly advocate using a standard coil, to stand the continuous voltage, rather than the application of external resistance with the coil. In fact, he must agree to that, because right below he says "strike for simplicity".

In regard to Mr. Stratton's paper, I might add a little weight of evidence if there is any one who doubts the advisability of calculating this matter of gearing. I will take one example I know of, the case of two trolleys, both of which have to make the same trip. The man who built the trolleys decided to make one for 1200 ft. per min., and the other for 1000 ft. per min. He turned the same amount of power on them, and the one geared for 1000 ft. per min. got ahead and remained ahead until it had gone 315 ft., and then the other passed it. Apparently in going less than 315 ft. one moved faster than the other, and in going more than 315 ft. the other moved the faster. I calculated that same thing, and the calculation showed the two time-distance curves crossed at 315 ft.

K. A. Pauly: I do not think I will say anything more than to emphasize the importance of making calculations in advance of the application of control. I had occasion at one time to look into an application similar to the one Mr. McLain referred to, where it was shown very conclusively that the lowers peed, or what appeared to be the lower speed, in the operating condition was actually the higher speed. The same thing was proved very conclusively at Gary, where the lifting tables were geared for a lower speed and actually operated faster.

I think there is a general feeling on the part of practical men, or so-called practical men, against the use of mathematics, as we often hear it said that the trouble with theory is that it does not work out in practise. I think the reason for that is purely the fact that in applying theories there has been a tendency in the past to generalize too much, to make assumptions where the facts were not known, and to assume that certain factors which were difficult to compute were negligible. I think that practise always conforms to theory, provided the factors involved are all included and properly taken care of; I think that a great deal of trouble and money can also be saved many times, which is spent in experimental work and in other ways due to disastrous failures. Much control equipment can be simplified if only a few calculations are made in advance, these calculations, of course, to be sound and to take into account at least all of the factors which are known to affect the problem.

As has been said before, the control is the nervous system of the motor application, and if the nervous system is unbalanced or not in good condition the whole application fails, as does the individual if his nervous system is deranged.

J. S. O'Donovan: I think that every operating electrical engineer, and also those who come in contact with the operation, will agree with me that the mechanical man makes a mistake on the proper ratio of gearing, without taking into consideration the calculations required to obtain the results. We had a little incident, about a year ago, which was quite simple. We bought a charging machine for a butt welding furnace. Other machines had been built by the same firm, but when we got the drawings in advance of the machine, I discovered that the full load speed of the travel of this charger in front of the furnace was 375 ft. per min. The machine with which it ran in conjunction on the other side of the furnace operated at 100 ft. per min. I called the company up by telephone and told them they would have to change their gearing on that machine. Instead of using a 25-h.p. motor to drive this particular machine in the rack, we substituted a 10-h.p. motor which was even larger than was necessary. This goes to show that the mechanical engineers who design almost all of these machines, are not very careful of the gear ratios. I think that if there were some way to bring the mechanical engineers in closer contact with the electrical engineer, we would get better results in the designing of our apparatus for use in steel mills.

Jacob F. Motz: I understand the papers on mill controllers are presented as follows—one from the manufacturer's view-point and one from the operator's view-point. You may consider this discussion as a salesman's view-point.

The first controllers used in steel mill work were street car controllers. The first of these was no more than a rheostat arranged to operate in conjunction with a reversing knife switch, and, by the way, very ingenious devices they were. It was not long before the manually operated controller, built especially for steel mill work, was developed in the steel mill. This controller still maintains its general characteristics, having been improved only along such lines as make it now a reliable piece of apparatus. The controller I have in mind is the face plate controller, having only a few fingers for adjustments, and arranged for straight line lever operation. There is one manually operated controller, which is used to some extent, known in steel mill parlance as the street car controller, or the drum controller. This type has a large number of fingers and a rotary motion of the handle for operation.

Naturally, there have been many variations and some widely scattered departures from these two designs, but the point I wish to make is this: There seem to be limitations attached to the manually operated controller.

While the papers of the day call almost exclusively for magnetically operated controllers, I believe there is still a small field for the manual controller. For instance, a new company with limited capital can begin operations with a smaller outlay by installing the manual controller. Then as the company prospers and continuity of operation becomes more exacting, the manual controller should be discarded.

Many old plants have not yet started to replace the manual with the magnetic controller on electric overhead traveling cranes, and the operating officials of these plants are not yet firmly convinced of the superiority of the magnetic controller for this service. One of the principal reasons for this attitude is due to the improper selection of the form of magnetic controller that has in some cases been made. This improper selection can be attributed to inexperience.

To my mind, there is a greater gain to be effected by installing magnetic controllers on cranes than on mill tables. There is one reason, however, why it does not seem so necessary: Cranemen are a more intelligent class of operators. The craneman of today should be an operator only. No longer is he the mechanic, electrician, or "jack-of-all trades," not even the inspector. The inspection can be done by one peculiarly fitted for the work. When any repairs are needed, a mechanic should be provided to do that work. Some one has succinctly said "the starter with brains." I will leave it for you to answer whether or not it pays to put "controllers with brains" on your cranes.

Just why was the magnetic switch controller developed? The first reason was because it was found that the more controllers one man could operate the better could these operations be kept in step with one another. To illustrate that fact, imagine four men trying to keep in step operating a modern soaking pit crane. There has recently been installed a soaking pit equipment where the cranemen even open soaking pit covers with the crane, not on account of the inability to obtain satisfactory equipment to perform this operation, but because no one but the cranemen must think about this operation. The smaller the number of men that have to act in unison, the more accurate will that action become.

It was impossible to assemble more than a limited number of manually operated controllers about one man, even though controlling levers were used, and, this being accomplished very easily by the use of magnetic controllers and their masters, there was but one thing to do—use magnetic controllers.

It would not take such a wild flight of imagination to think of one man actually controlling the complete operation of a blooming mill from the soaking pit to the shears. With such possibilities before us, I think it would not be well for us to go to too great lengths in order to make all controllers duplicates, because ultimately each controller will have its place and will be designed for some particular operation. There are no two applications that necessarily have the same cycle of operation. It seems correct to assume that each controller must be peculiarly fitted for the work in order to obtain the most efficient operation. Is it good engineering to put a 50-h.p. motor and controller on a job which only requires a 25-h.p. motor and controller? There has been too much ear given to the repairman simply because of wrong application of motors and controllers. Mr. Stratton has very correctly pointed out the vast difference in gear reduction used to connect the motor to its load, where the load and motor sizes remained the same. It looks as if this would be a good place for the electrical engineers to step in.

There are many reasons why the magnetic has displaced the manual controller, and also as there are many points concerning the actual make-up of the controllers and the construction of the individual units that go to make up the controller that need to be discussed, which I hope will give rise to lively argument, as these points are of most vital interest to the operating man.

S. C. Coey: I believe I am safe in saying that there have been more mistakes made in determining the proper gear ratio on mill tables than in any other application of electricity to the iron and steel industry. I have been very much interested in Mr. Stratton's paper, and hope to work out some of our existing installations to find out how they check up with his deductions. I would like to call your attention to two factors that enter into this matter of gear ratio, which this formula does not cover. These have been brought up before, I believe, but I would like to emphasize them. One is the variation in friction load. I have in mind one new mill table which, after it was in operation for a few months, operated so freely that the friction load was reduced to such an extent that it was necessary to cut out the last two points of acceleration on the controller and run it on resistance. This same table when it was new became so heated up with hot slabs lying upon it that the motor was not heavy enough to start the table, and it was necessary to get out the fire hose and cool it before it could be run. This shows the two extreme conditions in friction load, and they have to be taken care of.

There is another very important factor in this problem, and that is the distance through which the piece on the table or other apparatus controlled by the motor has to run in a cycle of operation. On a 44-inch blooming mill which we started up about a year and a half ago, we figured out as carefully as we could the gear reduction on the various parts of the mill. After it had been in operation a short time we found that a screw-down, which was operated by two 100-h.p. mill motors, connected permanently in series, was the slowest point in the mill. As Mr. Stratton has pointed out, the slowest point in the mill is the point that limits the production in that mill. This screw-down installation was gone over carefully, and I concluded, because we were moving the screws only from one-half to three inches on the down motion, and a maximum of 44 inches on the up motion, that quicker starting and not the full motor running speed of the screw was needed to speed up operations. We reduced the gear reduction on this drive 40 per cent. This would naturally, you would say, reduce the final speed of the screws by the same amount. As a matter of fact, this speeded up the operation of the screw-down so that it was able to keep ahead of the reversal of the machine. There is always some factor which is the limiting factor in the operation.

On this same mill we had the approaching and rear tables of the screw-down equipped with two 100-h.p. motors, permanently in series. On the front table we had twenty rollers and on the rear table fifteen, and we found that the front table was very slow and retarded the operation of the mill. In this case by changing the gear reduction again practically 33 per cent, and incidentally cutting down the normal running speed of the table 33 per cent, we increased the actual operating speed of the mill.

I believe Mr. Stoltz referred to this table in his remarks, and noted that by placing these motors in parallel we could increase the speed of the table again. But we had come to other limiting conditions. This mill has been running now about eighteen months, and when we started up we rolled in the first month about 200 ingots per 12-hour turn. That was gradually speeded up to 300 and 400 and 500. Just within the last month, by some changes on the manipulator finger control—the point which was holding us back—we have speeded them up and last night this mill turned out 564 ingots in twelve hours. It may be we will get to a point where that front table will have to be speeded up. Until we get to that point, we prefer to keep two motors connected permanently in series. With this connection, if any trouble develops on one motor we can throw double-throw switches over and run the mill on a single motor, until we can make the necessary repairs. Also it is a fact that in running two motors on a blooming mill you have less repairs when they are connected in series, than when running them in parallel.

The point was brought up this afternoon as to the advisability of keeping the back table motors stationary when running a blooming mill. Some rollers keep their back table motors stationary, some roll their back table motors with the piece, and some keep the back table rollers rolling in towards the mill. This last condition uses a minimum of power, with the maximum of wear on the roller surface. We find in actual operation that this condition allows the roller to get his piece ready for the next pass and reverse just in time to take the piece in to the rolls.

In regard to the use of dynamic braking, I may say that we have installed on this screw-down in question, dynamic braking, so that the motor will stop in a quicker time with dynamic braking than it will by plugging. That is the only method by which you can make a roller use dynamic braking on a screw-down, because if he can stop more quickly by plugging, and he is working on a tonnage basis, he is going to plug. That installation is now working very satisfactorily and it has been for some months.

I certainly agree with Mr. Riggs concerning the advisability of using a magnetic controller in a large number of cases. There are, however, still some applications where the manual controller is quite satisfactory. In a mill control, there is one point in connection with the use of automatic controllers which I think should be brought to the attention of manufacturers. In blooming mill practise nowadays you have two or three different operators using the same master controller at different times in the twenty-four hours, and it is on this matter of master controllers that the manufacturers have fallen down more than on any other point. The master controller should be so heavy, mechanically, that a man cannot break it, and I think that most of the steel mills in the country have designed master controllers of their own simply to get them heavy mechanically, so that they will be able to offer considerable resistance to abuse. In those cases where a man comes on and works eight hours, and is relieved by another man, and he in turn is relieved by a third man, it is hardly to be expected that each of these men will take the same pride in the apparatus, as if he were running a lathe in a machine shop, and was the only man to use it.

Another point regarding automatic control that has come to my attention of late, is the fact that in certain cases we have found that with automatic control we have practically eliminated the up-keep on motors and controllers; but, curious to relate, increased the trouble on the mechanical end. I have talked this matter over with various engineers, and the only solution we have come to that appeared to apply to the case was the fact that with a magnetic controller we get in most cases a very much greater first rush of current than we do with the manual control, that is, the initial rush which is represented by a small fraction of a second. In any reduction on spur gear drives there is a certain amount of back lash, and as the operator plugs the control, the taking up of the back lash gives a hammer blow, which is greater the further down you go in the reduction. It may be necessary, in order to overcome this defect in special cases, to introduce resistance so that as the reverse contactors come in only a very small amount of current will be allowed to flow through the motor instantaneously, and then the regular sequence of acceleration will be taken up.

In Mr. Riggs's paper he recommends on a control panel, in addition to the double pole contactors, a single-pole contactor on the other side of the line, and an additional pair of fuses. I believe that if we tried to eliminate every possible source of trouble we would get into altogether too many complications for successful steel mill operation, and I am of the opinion that putting in these extra fuses to overcome trouble on the contactors is an additional complication.

It has been suggested that instead of using contactor coils, shunt coils with external resistance, only continuous operating coils should be designed and put out. There is one point where continuous operating coils are liable to get the operating end into trouble, and that is on screw-down work, where a man makes very small movements. With a continuous operating coil he can get a condition where he just gives the coils sufficient of a start for the copper tips to touch, draw an arc, and freeze in. The only excuse for the external resistance in shunt coils is to get a snappy action in the coil, so that it eliminates, to a large extent, the possibility of touching the tips and freezing the contactors in.

Paul Caldwell: Regarding the last point brought up by Mr. Coey, I have a suggestion to offer, which will eliminate this trouble. A contactor coil wound for 125 volts with liberal overload capacity, will stand 220 volts applied intermittently on service as outlined by Mr. Coey. These coils will give the contactors the snappy action required of them on rapid reversing service and have been successfully employed for several years. A uniform installation can be made by using 125-volt coils for all classes of service, connecting them, two in series for ordinary service and directly to 220 volts for service first referred to.

Mr. Coey also mentioned a particular screw-down on which he has been able to secure faster operation by means of dynamic braking than by plugging. It has always been my opinion that dynamic braking is a negative or retarding torque whereas plugging is a positive torque applied in the reverse direction to rotation.

It seems to me, though Mr. Coey states he has accomplished this result, there might be some error in the calculations as to the time required to stop with the two methods, or there is some special feature which has not been mentioned by Mr. Coey. Personally, I believe that a positive torque, exerted in the reverse direction to rotation, will bring a motor to rest more quickly than a negative torque, such as dynamic braking, which loses its energy as the speed of the armature approaches zero.

With reference to Mr. Riggs's paper, in the tabulation for hot and cold saw work, he recommended a simple automatic push button control. I believe it would be better to add dynamic braking. A cold or hot saw will usually run several minutes after the motor is disconnected from the line, whereas with dynamic braking it would be stopped in a few seconds. This application has been successfully made and I believe the advantage gained from standpoint of safety warrants the additional expense.

Mr. Motz has brought up the question of manual control for cranes, and made some comparison between the dial type and the drum type, or what he terms the "street car" controller. The "street car" or drum controller has many distinct advantages which a dial type does not possess and I am glad to see that it is being more universally used for all classes of industrial work.

From the standpoint of safety, the drum controller affords complete protection to the operator, being entirely enclosed and having no live parts exposed. It is both dust and moisture proof, and can be successfully used for outdoor work as well as indoor.

On the other hand, nearly all dial controllers are unprotected, thus exposing the operator to contact with live parts.

There is always more or less arcing or flashing connected with the operation of these forms of controllers and blow-out devices are employed to minimize this and to insure the successful breaking of the circuit at the "off point." This is more successfully accomplished in the drum type controller by virtue of the fact that a flash board is used in connection with the blow-out which causes the arc to be directed away from the contact point and also prevents it spreading to adjacent segments or fingers. With the dial controllers, there is no means of controlling the direction of the arc and the result is a sputtering effect which produces a severe burning between segments. Also where the service requires the controller to break high peak loads, it is frequently necessary to provide magnetic switches to open and close the main circuit.

This continual flashing on a dial controller, especially where it is mounted directly in front of the operator, is not only dangerous but impairs the operator's vision and frequently results in permanent injury to the eyesight. This fact was brought out in a recent meeting of the Association of Iron and Steel Electrical Engineers, devoted to safety. It was also mentioned by one of the foremost steel mill engineers present that this flashing was so noticeable at night that the cranemen appeared to be exchanging flash signals instead of operating controllers.

In regard to making repairs, the drum controller is as accessible as the dial type. It is no more difficult to remove the cover from a drum controller and replace a clean finger or segment than it is to replace the badly burned segments or brushes of a dial controller.

When applied to hoisting service where dynamic braking is used, the drum controller will provide better operating characteristics than the dial type. On account of the construction of the dial controller, making it necessary to pass over the resistance segments in consecutive order in both directions of operation, its speed adjustments in one direction are limited by the speed requirements in the other direction. That is, any change of adjustment in speed values in the lowering direction necessarily changes the speed values in the hoisting direction. Vice versa, any change in the hoisting speed values also changes the lowering speed values.

With drum controllers these speed adjustments can be made independent of one another inasmuch as the resistance contacts need not be arranged in consecutive order and may be staggered to meet any conditions. This permits of one or more stops of resistance being used in the field circuit to secure high speeds when lowering without having this same resistance in circuit at all when hoisting.

With this flexibility of speed adjustments it is possible to secure a lowering speed with light hook of 150 per cent rated full load speed of motor and at the same time not reach a dangerous full load lowering speed or impose any limitations on the hoisting speeds.

I do not believe it is possible with a dial controller to come within probably 30 per cent of the high lowering speeds secured with a drum controller and not materially affect the speeds in the hoisting direction. I should like to know if it has been accomplished.

J. A. Albrecht: In respect to the dynamic brake controller on the screw-down, my experience has shown that Mr. Coey is right. It is not necessary, as Mr. Caldwell says, to wait for the tail of the curve on the dynamic brake. As you all know, when you apply the dynamic brake you get quite a rush of current which stays up for a time and then falls off very gradually. Where the time is lost in dynamic brake controllers is on the tail of the curve, where there is practically no braking action.

Mr. Coey also brought out the point that the operator, if he did not get the correct stop to his dynamic brake, would plug. By means of a double-pole contactor with one of the contactors doubled through the dynamic brake, by the back contact action, the back being closed by gravity and electrically sealed, we can prevent the reversal until the motor is practically at rest. But if we are willing to stand for a little plugging, by shunting the series coil which holds the dynamic brake contact closed, we can entirely eliminate the tail of the curve. We can get our effective dynamic braking action, and then at a certain point, probably at 50 per cent full load current or higher, if we desire, we can allow our reversing switch to close in the other direction, and thus cut off the tail of the curve and save considerable time. I think that method of screw-down operation has been conclusively proved to be the fastest drive.

T. E. Tynes: There is one point which has been touched on rather lightly this afternoon. Mr. Rushmore made mention of there being 5000 different motors of one type. I think we have about five thousand different motors of several types, and I want to put in a plea here this afternoon for standardization. Why cannot the motor builders, when they get a good thing, stick to it? The salesman calls me up on the telephone and says: " I would like to make an appointment to see you. I have a new type of motor I would like to explain to you and tell you of its merits," and my heart sinks within me. I can call to mind twenty different kinds we have in our plant, besides four or five different sizes of these different types, and you can imagine the time we have in keeping spare parts for these motors. We have to carry an enormous stock of supplies in the way of spares, and that means tying up quite a considerable amount of capital.

I think within the last four or five years, or less than that, there is not a motor manufacturer represented here but has changed his standard in some particular or another, just enough to make it impossible for us to apply some of the spare parts we have for the other types of motors, to these newer motors. Then when we buy this new type of motor, we immediately have to buy spares to secure the protection that the mill superintendent demands.

Mr. Motz spoke of its not being good engineering to apply a 50-h.p. motor to a 25-h.p. motor shaft. It may not be good engineering, theoretically, but I think it is good practical engineering to apply a 25-h.p. motor to control a 20-h.p. job, rather than to carry a special design of motor for that particular job. We have to look out for the investment side of it, as well as the theoretical engineering side of it.

K. A. Pauly: I will say one word in reference to what Mr. Tyne spoke of, because I think he hit the motor manufacturers a little too hard. In the first place, there are two reasons why the designs are so rapidly changed. The fundamental reason is the fact that the whole development of the art has taken place in such a short time that many of the old machines which were inefficient and inadequate to meet the needs of service are still in service. That means in most plants there are representatives of all stages of development. In the second place, the manufacturers of motors wish that the users of motors would standardize their practise. It frequently happens that when we get a motor standardized and we make quotations based on that motor, we are told that it is a little different from what some one else has quoted on, and that our proposition will not be acceptable unless we quote a motor as specified. There is cause for complaint on both sides, but the matter will straighten itself out when the art is older and there are not so many changes made in the motors.

W. T. Snyder: I was very much interested in Mr. Stratton's paper. I think these simple equations such as he gives are very good. They are certainly appreciated by the operating men; not that they should lean on these equations altogether, but to use them in a way, in connection with an ammeter, a voltmeter and a stop-watch. I mean to say they are good things to check up with. Sometimes we get rather suspicious of these theoretical calculations; but at the same time I do not think we want to take the stand that we desire to discourage them altogether. We do have use for them, and I want to thank Mr. Stratton for them. We would like to have some more of them.

I was very much interested in what Mr. Rushmore said about the five thousand different kinds of motors. There certainly could be a lot of work done in that direction by a well-balanced committee getting after a condition of that kind. I believe that if a committee, made up of controller users, motor users, representing the applications to which these motors are put, would go through these five thousand different types they could be reduced very materially. I do not believe any one of them could do it—I do not believe the controllers can be cut down by themselves, and I do not believe that the motors can be cut down by themselves to any great extent. All of the factors must be taken into consideration.

In regard to mistakes in application, particularly roll tables, that Mr. Coey referred to, I was just wondering whether he should not say that most mistakes which have come to notice have been made on mill tables and screw-downs. That application is pretty close to the management, and a mistake made there is generally known, but I do not believe it is the only place where mistakes have been made.

I happen to recall a crane, which was hard pushed to keep up with the mill, not so much on account of the speed of the crane, as the continuity of operation, and the mill management wanted to know if something could not be done. By the time they got a roll ready they did not have any crane; on account of trouble with the controller, trouble with the brake, trouble with the motor, and trouble with upsetting the lifts. We analyzed the condition and decided to cut down the speed by changing the gear reduction on the hoist motor and also on the trolley motor, and now when we are feeling blue about something else we go around and ask the mill manager how his crane suits him, and he says it is the best he has ever had. The same thing applies to delivery tables for the mills. We probably have delivery tables running, taking but a fraction of a minute to deliver the material from the mill, and it takes the mill a minute and a half to roll the material, and what is the use of getting the product away from the mill in a few seconds, and then have the table shut down or running idle? I think it is better to slow down the table and let it carry the product away from the mill at the rated speed. This would apply particularly to a plate mill table where there must be a certain amount of cooling, which may as well be done on mill tables as on the cooling bed.

Mr. Coey made reference to the trouble with master controllers. I can bear him out on that point, not only with respect to master controllers, but push-buttons. We had a good deal of trouble in getting a push-button that would stand up. The push-button and the master controller are the nearest things to the operator and about the only things an operator can abuse in connection with an automatic controller. We know that the operators, as well as ourselves, get out of humor sometimes, and very often the master controller or anything that is handy has to suffer. There is a good deal of trouble from that source—the mechanical weakness of master controllers and push-button switches.

Mr. Pauly brought out the point that this matter of standardization is not up to the manufacturers. I quite agree with him there. The manufacturers are going to give the purchaser just about what he wants, provided the purchaser will pay the price. All must work together on that subject.

In further reference to the matter of standardization of magnetic controllers, I would say that the Association of Iron & Steel Electrical Engineers have this matter up through their Standardization Committee, with an idea of starting in to standardize the simpler types of controllers. It seems to me that with the controller properly standardized, we should be able to offer a controller of a certain type, instead of specifying a 30-h.p. controller, which has to be idle so many minutes a day and so many minutes a day busy, and things of that kind. We would be able to specify, for instance, a screw-down controller for a certain size blooming mill of a given capacity. Specifications should be given to the different manufacturers so that we should be able to call for 10-ton cranes for ordinary service, hard service and the like. We should also be able to call for a controller for a 10-ton machine shop crane, and a controller for a 10-ton foundry crane, and these two controllers would probably come off the same shelf. I think that controllers could be standardized along that line and make it much simpler for everybody concerned.

K. A. Pauly: With reference to the question of the number of standard motors, the following figures may be of passing interest—take, for example, a line of induction motors, and consider only one size, from 1 to 200 h.p., inclusive. There are approximately fifteen different capacities which must be designed for five different voltages, 110, 220, 440, 550 and 2200, making seventy-five in all; three frequencies, 25, 40 and 60 cycles, which raises our number to 225. The speeds required will probably average about four, which again increases this number to 900. Water resisting, fire resisting and ordinary insulation will probably average about two per size, making the total 1800. Allowing two as the average for open, enclosed and semi-enclosed, vertical, horizontal, etc., our figure is 3600. Then the types used for crane, mill, constant rating with other special ratings, will approximately double this figure, making it 7200. Then if we consider the broad subdivision of squirrel-cage and polar wound rotors, it will approximately double this, making our total 15,000.

I think the manufacturers will all appreciate any suggestion from the users as to where we are to begin to make the reduction.

H. D. James: In discussing the question of standardization I think a word of commendation should be said for the steel mill engineers. About ten years ago the application of electricity to steel mills was being seriously considered and the development was becoming quite extensive. The electrical engineers of the steel mills organized and standardized a considerable number of their requirements, such as the speeds of motors, voltages, etc. This has helped the manufacturers in producing better apparatus and making better deliveries.

Undoubtedly the manufacturer would like the customer to state his requirements, but he must assist the customer, as the result is a question of adjusting manufacturing conditions to accomplish the wants of the customer. During the past ten years a great deal of information has been obtained by tests and the tabulation of data which enables the electrical engineer to apply motors to the various operations in the steel mills with as much, if not greater precision, than the application of motors to traction work. In a number of cases the electrical engineer has been able to guarantee the kw-hr. required to roll a ton of metal.

Mr. Stratton's paper is entitled "Mill Controllers" but it deals largely with motors. I think this is perfectly proper because if the motor is not properly selected it is very difficult for the controller engineer to furnish apparatus that will give satisfactory results for the equipment as a whole. The controller simply supplies the functions which the motor itself does not have inherently in its own design. I believe we are getting closer to the solution of electric drive when we discuss the motor and controller together as we have been doing here this afternoon.

I hope that business conditions in the electrical industry will enable the manufacturers to cooperate still further with the operating men so that fewer sizes and varieties of motors and controllers will be required. This will not only benefit the manufacturers but will reduce the number of spare parts required by the customer.

Graham Bright: I wish to say a few words more in defense of the manufacturer. The condition in motor design can be compared somewhat to the fight between large guns and armor plate. Every time some fellow brings out a new armor plate the gun makers get busy and bring out a gun to put a hole through it. That has kept going on for years, and is the reason why neither armor plate nor guns become standardized. Every time the motor manufacturer comes out with something a little better, another manufacturer attempts to improve on it, and so it goes on. If the art of steel manufacture were at a standstill, the manufacturer of motors could bring out a line of motors which could be standardized; but the steel mill art is being improved right along. As fast as we bring out a motor which will meet a certain set of conditions, the mill operators immediately establish a new set of conditions, more severe in many cases. This makes it necessary for the manufacturer to immediately get busy and bring out a new motor to meet these conditions, so we are not altogether responsible for these many changes in types of motors. It is merely caused by the advance in the art of both steel making and motor design and will probably continue for some time. It is hardly probable that any standardization will be such that a set of motors will be brought out that will last for ten years without change.

W. H. Markland (by letter): I am very much pleased with the improvements that have been made in motor control in the last few years, especially the so-called push-button control as applied to d-c. motors. These are reducing the repair account both for motor and rheostats as compared to the old dial and drum types of control.

In some respects it would appear that the machine tool builders when applying motors do not give the question of control the attention it deserves. On several machines made by good concerns the rheostat appears to be located anywhere and not in reference to handy reach.

On a number of machine tools the friction clutch is employed. Where a d-c. motor is used this could be profitably done away with by employing a standard make of push-button control with push-buttons placed convenient to the operator. This will result in a saving of current as the motor would be idle when not cutting, in place of present practise of running motor light.

One method of remote control that was new to the writer in application may be of interest. A six-foot drill press of standard make was worn from long continuous service and was returned to the makers for general repairs and application of d-c. motor. A motor was applied in the customary manner except that the customary friction clutches for controlling forward and backward rotation of drill spindle were omitted; that is, the power was transmitted from motor to spindle through the customary gears and shafts. The motor was variable speed and was controlled for forward and backward rotation by a switch similar in general appearance to a drum controller, this being placed on the drill spindle housing directly in front of the operator; also a field control rheostat was placed near the motor. When the handle of control switch is in horizontal position the motor is at rest, or if thrown from either running position to this position the dynamic brake is applied. Handle in down position, motor runs forward—up position, backward. Between horizontal and up or down the motor comes to rest slowly. It has been found that the drill press can be reversed in a fraction of a second and that it is entirely safe for tapping holes and has all the advantages of the former clutch arrangement without the disadvantages. When not drilling, the motor is at rest, as it takes very little effort on the part of the operator to stop the motor. There is nothing new or novel in the motor control and similar outfits may be bought from several concerns.

In these days of sharp competition it is quite essential to reduce the labor of the tool operator as much as possible and with a proper arrangement of control apparatus a large number of steps may be saved in the course of a day's work.

Palmer Collins (by letter): The development of electrical apparatus for use in steel mills has resulted in a wonderful improvement in methods of handling auxiliary apparatus and has resulted in the use of types of apparatus which would be impractical without the use of electrical drive. Mr. Stratton, in his paper on mill controllers, has given some of the reasons for benefits to be derived from electrical apparatus, and I think in addition to those he gives, there are two other results of the use of electrical apparatus in a steel mill which are of great importance. An electrical system, unlike a direct engine or a hydraulic drive, has no definite maximum capacity. The individual motors can have several times the capacity of the generating station, which can take care of peak loads without trouble, as can also the individual motors. The engine or hydraulic drive has a fixed point of maximum power and fails when called upon to give more than this to take care of any extraordinary condition. In addition to this, the electrical drive of auxiliaries such as roll tables, etc., practically always results in a reduction both in the cost of repairs and in delays caused by breakdown of the apparatus itself. This is due to the improved starting characteristics of the motor, particularly if it is equipped with automatic control.

I believe that the use of automatic control is of great importance in steel mill service. I have installed it on main roll drives, heavy hot metal open-hearth cranes, reversing roll tables and all kinds of miscellaneous motors down to ½ h.p. I believe that in practically all cases it is superior to any kind of hand controller. Considering the type of men who necessarily handle motors, it is much safer and its use undoubtedly results in less trouble with motors and machinery. My experience with these self-starters has, on the whole, been very satisfactory, but occasionally I have had experience which led me to believe that the manufacturers have not kept in mind the number of times which this apparatus is used per day and the wear and tear caused by the continuous use. In consequence, the apparatus has been built too light for the service. This applies even to the latest design of apparatus by some manufacturers. I have found in both self-starters and hand starters of several manufacturers a relay in the shunt field of a starter for a compound motor. This has invariably caused trouble, particularly if the motor is subject to quick variations in load, as this relay is very liable to be de-energized by the sudden increase in load on the motor.

I think that Mr. Stratton's point in regard to the slipping of the rolls on the material is very well taken, as it is my experience with the reversing roll tables, that the rolls slip on material considerably and that the acceleration of the motor and table is liable to be much faster than is necessary. Where an engine drive of reversing mill tables has been replaced by motor, this is particularly liable to be the case, as the information is based on data derived from the engine performance and may be biased by the anxiety of the mill operator to insure quick operation.

C. D. Gilpin (by letter): I wish to congratulate Mr. Stratton on showing us that mathematics as applied to steel mill engineering may not be as mysterious and impractical as most of us think. The method of regarding all the properties of the mechanism as concentrated on one shaft is one which the writer has found almost essential when making an analysis of the performance of certain high-speed mine hoists. There is an element that enters into these calculations, however, that Mr. Stratton has not touched on, but which is likely to be somewhat puzzling. This element consists of the friction losses in the gears and countershafts, and is often taken as a constant quantity. When so taken, it may be added to the actual load torque, and this is undoubtedly the best way to work out an approximate solution. Actually, however, the friction varies with the amount of power which is transmitted through the gears, and in cases where great accuracy is required it is necessary to consider this feature.

The writer wishes to take exception to Mr. Stratton's conclusion in which he states that the kilowatt-hours necessary to move the machine any number of revolutions is least when the time, t, is a minimum. This is true through a certain variation in time values, but when t is reduced below the critical point, the kilowatt-hours will again begin to rise. My conclusions in this matter are based on Mr. Stratton's equation (**6**), which is as follows:

$$t = \sqrt{\frac{4\,\pi\,N\,(I_1 + I_2\,r^2)}{g\,(Tr - F)}} \quad \text{or,} \quad t = \sqrt{\frac{4\,\pi\,N\,(I_1 + I_2\,r^2)}{gr\;T - gF}}$$

Let the numerator of the quantity under the radical be represented by k_1, while the quantities gr and gF may be represented by k_2 and k_3 respectively. (All of these three terms are constants for any particular case).

Then,

$$t = \sqrt{\frac{k_1}{k_2T - k_3}}, \quad t^2 = \frac{k_1}{k_2T - k_3}, \tag{a}$$

$$k_2Tt^2 - k_3t^2 = k_1 \quad \text{and } Tt^2 = \frac{k_3}{k_2}\,t^2 + \frac{k_1}{k_2} \tag{b}$$

Let work be represented by Ttp, in which the constant p is merely a conversion factor between torque and amperes input.

Then, work $= W = Ttp$; and $Tt^2 = W\dfrac{t}{p}$

Substituting in equation (**b**), $W\dfrac{t}{p} = \dfrac{k_3}{k_2}\,t^2 + \dfrac{k_1}{k_2},$

and $W = \frac{pk_3}{k_2} t + \frac{pk_1}{k_2} t^{-1}$; differentiating,

$\frac{dW}{dt} = \frac{pk_3}{k_2} - \frac{pk_1 t^{-2}}{k_2}$. Equating to 0 to obtain the minimum value of W, $\frac{pk_3}{k_2} = \frac{pk_1}{k_2} t^{-2}$, $t^2 = \frac{k_1}{k_3}$; substituting in (**a**),

$$\frac{k_1}{k_3} = \frac{k_1}{k_2 T - k_3}, \quad k_3 = k_2 T - k_3, \quad T = \frac{2k_3}{k_2} = \frac{2gF}{gr} = \frac{2F}{r} \qquad \textbf{(c)}$$

This indicates that to keep the expenditure of energy to a minimum, the acceleration torque and the load torque should be equal. Applying equation (**c**) to Mr. Stratton's equation (**15**),

$$r = \sqrt{\frac{I_1}{I_2} + \frac{F^2}{\left(\frac{2F}{r}\right)^2}} = \sqrt{\frac{I_1}{I_2} + \frac{r^2}{4}},$$

$$r^2 = \frac{I_1}{I_2} + \frac{r^2}{4}, \quad \frac{3}{4} r^2 = \frac{I_1}{I_2}, \quad r = \sqrt{\frac{4I_1}{3I_2}} \qquad \textbf{(d)}$$

It may be interesting to substitute in this equation the constants used in the example worked out by Mr. Stratton. We will then have the equation

$$r = \sqrt{\frac{4}{3} \times \frac{2892}{272.3}} = 3.75$$

which happens to be close to the value obtained by Mr. Stratton (3.46) for the best value for quick starting and stopping.

It would be interesting to work out the current curve of the mechanism for which Mr. Stratton has given the constants, assuming that the countershaft must make a given number of turns, and using both the old gear ratio and the new ones developed by Mr. Stratton and myself. Such an analysis, however, would take a considerable length of time and could not be considered as a general case. Owing to the varying speed characteristics of the series motor, it is impossible to work out any general formulas except for acceleration and retardation. For this reason also it is impossible to develop any general expression for the heating of series motors.

It should be borne in mind, of course, that the primary object of the gearing of steel mill machinery is not to keep the power input and heating of the motor to a minimum, but is to facilitate the handling of the steel at the highest practicable rate, as is very ably developed in Mr. Stratton's paper.

Presented at the 308th meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 16, 1915.

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CONTROL OF DIRECT-CURRENT HOISTS IN IRON AND STEEL MILLS

BY G. E. STOLTZ AND W. O. LUM

ABSTRACT OF PAPER

The control problem discussed in this paper is confined entirely to a typical example of a skip hoist. An outline of the conditions existing in the case of this particular application is given in which the load on the hoist is divided into three parts, namely, the friction load, the inertia of moving parts, and the useful work in hoisting the net load. The proper cycle of operations is determined, which in turn determines the required characteristics for the motor and controller which are together considered as a unit. The details of this d-c. skip hoist control are described and illustrated.

THIS SUBJECT would, in general, confine our discussion to skip hoists, cranes and ore handling machinery, the operation of each being sufficiently different from the others to warrant individual consideration. To treat each of these applications properly would require too much time, so it has been decided to confine our discussion to a typical example of a skip hoist.

In order to design control apparatus intelligently for an application of this kind, it is necessary for the engineer to understand fully the function of the various parts of the driven apparatus as well as the operating characteristics of the electrical machinery. We will therefore outline the existing conditions of this particular application, and then suggest a control which seems best to meet the definite requirements set forth.

SKIP HOISTS

Fig. 1 is an illustration of a typical hoist which has been selected for consideration in this paper. The load on a skip hoist can be divided into three parts, namely, friction load, inertia of the moving parts, and useful work in hoisting the net load.

The static friction at the moment of starting is, of course, greater than the running friction, but it is a comparatively small item, and with the machine in approximately continuous operation the static friction is not excessive, so that it is ordinary practise not to differentiate between static and running friction in calculating the load cycle. No formula can be used to determine definitely the friction, but various empirical rules are employed which approximate the true values sufficiently close to that obtained on hoists under normal operating conditions.

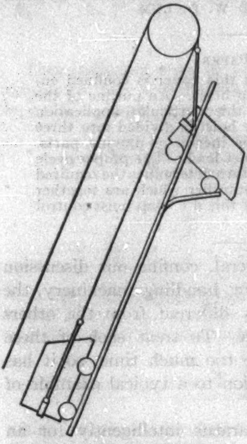


FIG. 1—SKETCH OF TYPICAL SKIP HOIST

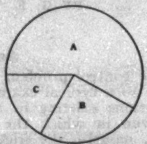


FIG. 2—CHART SHOWING RELATIVE INERTIA VALUES OF MOVING PARTS

A—Motor armature
B—Drums
C—Cars and ropes

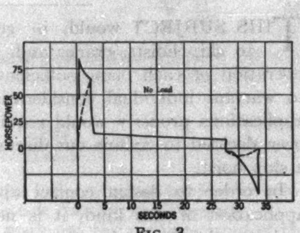


FIG. 3

The next item involved is the inertia of the moving parts. The apparatus involved consists of the drums, sheaves, gearing, armature, ropes, skips, and net load. The energy required to overcome the inertia of a moving body varies directly as its weight and as the square of its velocity. Therefore to minimize the starting and braking peaks, care should be exercised in the design of the apparatus. The diameter of the rotating parts should be kept as small as possible consistent with good mechanical design, as the velocity of these parts is a direct function of the diameter. This feature is characteristic of reversing mill motors, which are designed long and small in diameter to reduce their flywheel effect.

The weight of the armature is comparatively small, but its high velocity makes it an important item, as is indicated in Fig. 2.

The skip will occasionally be operated empty, the cycle being approximately as indicated in Fig. 3. The normal operation of this particular skip is two loads of coke, net weight 3000 lb. each, two loads of limestone, 3000 lb. each, two more of coke and four loads of ore, 6000 lb. each. This cycle will be varied to obtain satisfactory distribution of the material in the furnace, but is sufficiently near the average operating conditions for our purpose. Occasionally a load of scrap weighing 9000 lb. will be hoisted, but this is rare and need not be taken into consideration except as an overload for a few seconds. Fig. 4 graphically illustrates the load cycle when hoisting a 3000-lb. load. The curve is plotted between time, expressed in seconds, and torque expressed in equivalent horse power. During the accelerating period the dash line AB represents the actual mechanical output of the motor, but, since we are interested in the current taken from the line, all energy values will be expressed in the horse power equivalent of torque. The area enclosed in the triangle ABC represents the energy dissipated in the starting resistors during the accelerating period. This is one-half of the total input while coming up to full speed, as indicated in Fig. 5.

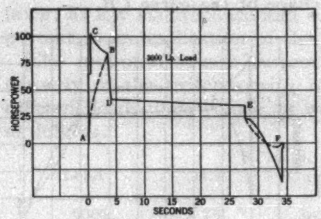


FIG. 4

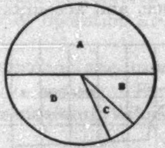


FIG. 5—CHART SHOWING DISTRIBUTION OF ENERGY WHEN ACCELERATING 3000-LB. LOAD

A—Rheostatic loss C—Friction

B—Inertia D—Useful work

It will be noted in Fig. 4 that the initial peak is only 66 h.p., whereas we would naturally expect it to be 105 h.p. This is the result of lifting the top skip off its track.

Before dynamic braking was introduced, with magnetic control, it was necessary to lift the skip two to four inches off the track when hoisting light loads to make sure the heavy loads would rise to a sufficient height to dump. At present dynamic braking can be made severe enough to practically stop all loads at one position. There is nothing to gain by doing this, and the rope is therefore adjusted normally to lift the top car off the track a few inches. This utilizes the whole car as a counterbalance and helps to land the skips more carefully. When the cars are again started the top skip still acts to its full capacity as a counterbalance and reduces the initial current peak accordingly.

On a vertical hoist the line *CB* would be straight, the difference in height of the two points being due to the transfer of the weight of the rope from the load to the counterbalance side of the hoist. During the acceleration period the top car comes down over the knuckle, which changes its effect as a counterbalance, and accounts for the shape of the curve *CB*.

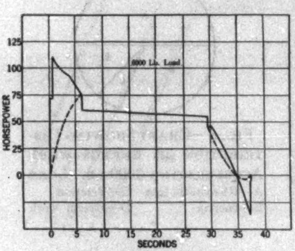


Fig. 6

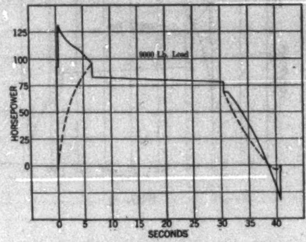


Fig. 7

The line *DE* represents the load when hoisting at constant speed. As the loaded car rises and the empty skip lowers, the net weight of the rope gradually favors the counterbalance and decreases the energy taken from the line.

During the period *EF* it is proposed to operate the control to obtain a gradual slow-down. When the loaded car goes up over the knuckle and starts to dump very little energy is required to continue its travel, as indicated by the shape of the slow-down curve. During this period we have friction and net weight acting against the inertia of all moving parts. If the latter is not sufficient to carry the car to its destination the motor will take energy from the line. Just before the cars reach their final position, dynamic braking should be introduced to bring the apparatus to a stop, at which time the line switches should be opened and the holding brake applied.

Fig. 6 represents the 6000-lb. ore load, and Fig. 7 the occasional 9000-lb. scrap load. Both are developed in the same manner as Fig. 4. The time of acceleration increases with the load, as the series switches will not operate so rapidly as with light load.

The interval of time between hoisting varies considerably, but the capacity of the control installed is determined by the maximum demand, which generally occurs after a breakdown. If the skip is not in operation for a period of time, the burden in the furnace may become so low that two or three hours are required to bring the furnace back to its normal condition. The rating of the control should therefore be based on the regular cycle of hoisting the 3000-lb. and 6000-lb. loads with an average interval between trips of eight seconds. The apparatus will then be somewhat liberal for ordinary operating conditions, but this is a point which should be received with favor, as low maintenance and continuity of operation are important in an application of this type.

The root-mean-square current will determine the carrying capacity of the switches with reference to heating. For the different loads these values, as well as the maximum values, are as follows:

	R. M. S.		Maximum	
Load	H.P.	Current	H.P.	Current
9000	76	300	128	500
6000	57	240	110	430
3000	42	182	102	400
Friction	24	116	83	334

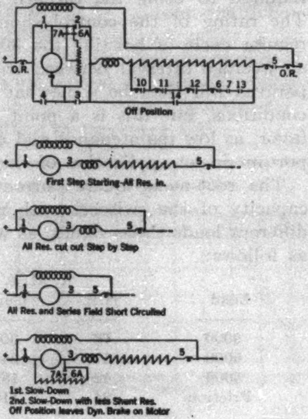
The average heating current taken from the line during the heaviest cycle of hoisting the 3000-lb. and 6000-lb. loads is 210 amperes, and the maximum is 430 amperes. The accelerating switches can open immediately after the last switch is closed so that they only need to carry an average current of 380 amperes, for a short time during each cycle.

The slow-down switches should be designed to handle the current adequately during this period of the cycle. The values actually obtained depend somewhat on the method employed in bringing the apparatus to rest.

Resistance will be required during the starting and retarding periods. An average of 220 h.p-sec. must be absorbed during the starting period of each cycle, and 600 h.p-sec. when retarding.

Fig. 8 shows a sequence of control, starting at rest and accelerating the motor to full speed, then the slow-down and stopping of the load.

The acceleration of the motor is controlled by a current-limiting device. For this reason the amount of current taken by the motor on the first notch must be sufficient always to start the motor with the maximum load of 9000 lb. This means that the starting current should be something more than the value required to start the load under ordinary conditions, so as to take care of tight bearings and other variations in the load.



Off Position

First Step Starting-All Res. In.

All Res. cut out Step by Step

All Res. and Series Field Short Circuited

1st. Slow-Down
2nd. Slow-Down with less Shunt Res.
Off Position leaves Dyn. Brake on Motor

FIG. 8

The number of accelerating points that is required will be determined by the maximum current peaks permissible. The number will also depend upon the characteristics of the particular motor used. It has been found in practise that six accelerating switches usually give satisfactory results on hoists of this character, with motors of 100 to 200 h.p.

Series-wound switches may be used for all but the last accelerating notch. This last notch should be a shunt switch or its equivalent. This switch is used for short-circuiting the series field of the motor, and it is very important that the switch remain closed after the motor has been brought up to full speed. There are conditions of operation which may cause the motor to regenerate, which will reverse the current and cause the series switch to open.

After the skip has reached full speed and approaches the end of its travel, the motor must be slowed down in order to make an accurate stop. The diagram shows the slow-down is effected by connecting a resistance in shunt with the armature of the motor and opening all of the accelerating switches, which inserts the series field and starting resistance between the motor and the line. The second slow-down step consists in reducing

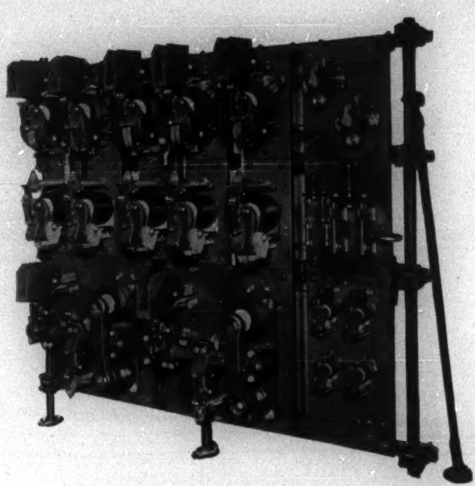


FIG. 9—FRONT VIEW OF SKIP HOIST PANEL [STOLTZ AND LUM]

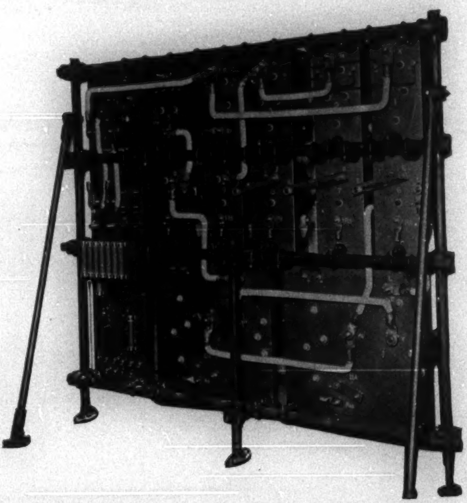


FIG. 10—REAR VIEW OF SKIP HOIST PANEL [STOLTZ AND LUM]

the resistance in shunt with the armature. This shunt resistance causes a definite current to flow through the starting resistance and series field of the motor. This shunt current is independent of the load and the current taken by the motor, so that a low voltage is impressed across the motor terminals. This slow-down should exist for a period long enough to enable the motor to reach a constant speed before it is finally stopped. The motor is stopped and the mechanical brake applied when the line switch is opened; the resistance is maintained across the motor armature and the shunt field is energized so that a dynamic brake is obtained in addition to the mechanical brake. The acceleration and slow-down are obtained automatically by means of proper switches attached to the hoist mechanism. The motor, however, can be controlled entirely from the master switch when desired. If the skip hoist should fail for any prolonged period while the furnace is in service it will result in serious damage, and for that reason every precaution should be taken to prevent a failure with the electrical equipment. The master controller and limit switches should open both sides of all coil circuits and the shunt brake circuit, so that a ground or other disturbance on the control wire will not prevent the motor being brought to rest.

In equipping the skip hoist, or for other applications where it is necessary to perform a definite cycle of operations and insure the customer against failure, it is very necessary to consider the motor and controller as a unit. The amount and kind of material forming the magnetic circuit of the motor will introduce a time element. The design of the motor itself may fit the amount of current used during different parts of the cycle. The function of the controller is solely that of furnishing the motor with the assistance the motor requires in going through its cycle of operation. As the design of the motor is improved, some of the functions of the controller may be incorporated in the motor, and the controller simplified. In slowing down and stopping the motor, most of the stored energy is in the armature of the motor. This item must be considered carefully so that the design will give a positive and accurate stop without imposing too great a strain upon the brake.

the resistance in shunt with the armature. This shunt resistance causes a definite current to flow through the starting resistance and series field of the motor. The shunt current is independent of the load and the current taken by the motor, so that a low voltage is impressed across the motor terminals. This slow-down should exist for a period long enough to enable the motor to reach a constant speed before it is finally stopped. The motor is stopped and the mechanical brake applied when the line switch is opened; the resistance is maintained across the motor armature and the shunt field is energized so that a dynamic brake is obtained in addition to the mechanical brake. The acceleration and slow-down are obtained automatically by means of limit switches attached to the hoist mechanism. The motor, however, can be controlled entirely from the master switch when desired. If the skip hoist should fail for any prolonged period while the furnace is in service it will result in serious damage, and for that reason every precaution should be taken to prevent a failure with the electrical equipment. The master controller and limit switches should open both sides of all coil circuits and the shunt brake circuit, so that a ground or other disturbance on the control wire will not prevent the motor being brought to rest.

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DIRECT-CURRENT CONTROL FOR HOISTING EQUIPMENT IN INDUSTRIAL PLANTS

BY W. T. SNYDER

ABSTRACT OF PAPER

In selecting a controller for application to various types of mill machinery all the conditions must be considered, such as the class of operator, conditions of location, operation and maintenance, relative importance of reliability, simplicity, cost of repairs, etc., and initial cost. These points are illustrated by three different types of control as applied to a blast furnace skip hoist, to a high-speed coal hoist, and to a low-speed ash hoist. In the first case reliability and continuity of operation are imperative, and other requirements are of secondary importance; in the second case, where an ordinary delay does not affect plant operation, questions of simplicity, repairs, maintenance and initial cost can be given more consideration, as continuity of operation is not absolutely essential; in the third case where the operations are performed by unskilled labor the most important requirements are that the controller perform its functions positively, accurately and automatically, and it should be provided with all the necessary protective features to avoid damage to the apparatus controlled.

IT IS the purpose of this paper to describe briefly the controllers on a few different types of hoisting equipment, and point out some of their advantages and disadvantages, also to point out what, in the writer's opinion, are good points to be desired, as well as the undesirable features to be avoided in selecting a controller for the different classes of service.

BLAST-FURNACE SKIP HOIST

A description of a particular skip hoist and controller is given below, Fig. 1 showing a general arrangement of the skip, cars, and hoist.

The hoist is driven by a 175-h.p., 300-rev. per min., 230-volt, compound-wound d-c. motor, geared to two drums, each mounted on a common shaft. One of these drums winds up the hoisting cable while the other is unwinding, one car being at the top of the incline when the other is at the bottom.

When the power is shut off the hoist, a solenoid-operated band brake is automatically applied. The solenoid is shunt-wound and is energized by the closing of the reverse switches, and released upon their opening. The amount of power and time required through an operating cycle are shown in Fig. 2.

As is shown on this curve, which was taken under normal operation, the time required to hoist the car to the top of the furnace and dump it is 40 seconds. If for any reason faster charging is desired, this time can be reduced to 33 seconds per trip by adjusting the accelerating relay to shorten the time for acceleration, and also, by making a slight adjustment, resistance is automatically inserted in the shunt field circuit immediately following the last point of acceleration, and is cut out again just before reaching the normal slow-down point. When not needed, it only requires a moment to make the necessary adjustments to allow the hoist to operate at normal speed.

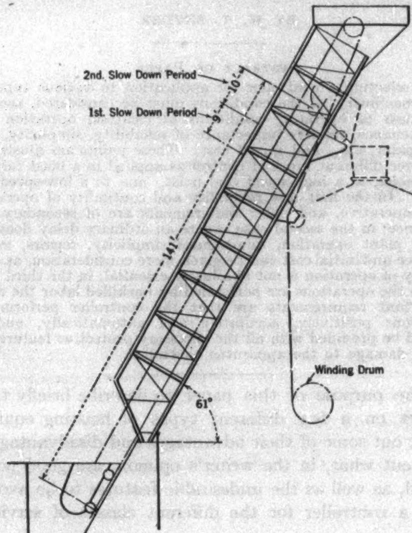


Fig. 1—Skip Hoist for 500-Ton Blast Furnace

Should the hoist cable become slack for any reason, such as a descending car stopping on account of derailment, broken axle, etc., before it reaches the bottom, or if one of the duplicate cables should break, the sagging cable will open an electrical contact which will immediately cut off the power, and the motor comes to rest.

To the hoist drum shaft is geared a contact arm which travels over a dial on which there are contacts that control some of the operations of the main controller after the operator, who is located forty feet away, throws on the master controller to start.

To the motor shaft is connected a small generator, the voltage of which varies with speed of the hoist up to 70 volts maximum. Across the terminals of this generator is connected a relay which varies the resistance that is connected in multiple with the armature of the hoist motor at the slow-down point. This is accomplished by adjusting the relay so that it will operate when a load of coke or an empty car is being hoisted, and cut out at this point a section of the resistance that is connected in multiple with the hoist armature.

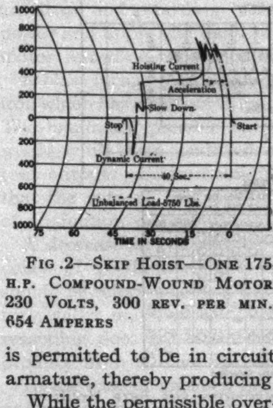


FIG .2—SKIP HOIST—ONE 175-H.P. COMPOUND-WOUND MOTOR, 230 VOLTS, 300 REV. PER MIN., 654 AMPERES

When a heavier load is being hoisted, the speed of the hoist is reduced, in consequence of which the voltage from the small generator is not high enough to operate the relay, and all the resistance is permitted to be in circuit across the terminals of the hoist armature, thereby producing less retarding effect at this point.

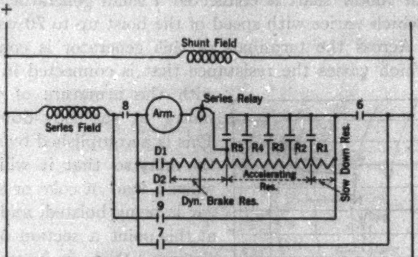
While the permissible over-travel is 28 in., the actual variation in the stopping point, with this simple slow-down arrangement, does not exceed five in., and is due to the slip of the brakes on the various weights of load.

A simplified wiring diagram of the connections of the motor and controller, and a chart showing the sequence of operation of controller switches, are shown in Fig. 3.

This controller is located in the same building as the hoisting machinery. It is inspected and given any necessary attention the same as all other electrical apparatus.

During the past four years, the entire electrical equipment in connection with this skip hoist, including motor, controller, and wiring, has caused a stop of 55 minutes on the furnace, and was due to paraffine running out of a relay coil and getting on a secondary contact, thereby insulating the contact and causing the controller to fail to start. Most of the time was spent in hunting the trouble. With proper arrangement of terminals this fault could have been found by test in a very short time.

When it is considered that the skip averages 16 trips per hour, seven days each week, and that the controller goes through the different operations of the cycle each time entirely automatically—accelerates, slows down, and stops, with no further attention after it is started by the operator closing the master switch, the degree of reliability that can be obtained with a modern controller is evident.



Sequence of Switches

No.1 Skip Car Up No.2 Skip Car Down										No.1 Skip Car Down No.2 Skip Car Up							
Sw.	Slow Down			Accelerating					Off	Accelerating					Slow Down		
R1	2nd.		1st.	○	○	○	○	○		○	○	○	○	○	1st.	2nd.	
R2				○	○	○	○				○	○	○	○			
R3				○	○	○						○	○	○			
R4				○	○								○	○			
R5				○										○			
6	○	○	○	○	○	○	○	○									
7										○	○	○	○	○	○	○	○
8	○	○	○	○	○	○	○	○									
9										○	○	○	○	○	○	○	○
D1	○	○														○	○
D2	○																○

Switch D2 Automatically Selected

FIG. 3—SCHEME OF MAIN CONNECTIONS FOR SKIP HOIST

The master switch being located remote from the main controller and hoist apparatus makes it inconvenient to maneuver the hoisting machine when changing or adjusting cables. This objection was overcome by providing simple hand control in the hoist house, consisting of several small knife switches connected to the main controller. A single-pole, double-throw knife switch operates the reverse contactors; another single-pole, single-throw knife switch operates the accelerating switches, and another switch of the same type operates the slow-down contactors. This arrangement, in addition to convenience in maneuvering the hoist, permits the electric repairmen to try out the main controller after any adjustments or repairs without being required to signal some person to operate the master switch. The scheme has the advantage over a duplicate master switch in that any operation of the main controller can be performed out of its regular order.

To prevent the car from approaching the stopping point at a dangerous speed, a relay is provided in circuit with the hoist armature and retarding resistance, that will operate to cut off power and apply the band brake should the circuit through the motor retarding resistance not be made at the proper time.

A blast furnace can produce continuously a certain amount of iron which has a certain value, dependent upon market conditions. The maximum possible output under best possible conditions would, while these conditions remain unchanged, result in 100 per cent output. Certain conditions arise, however, which require that the rate of melting be reduced, which results in loss of production commonly and erroneously termed delay.

A decrease in the rate of the melting process results not in delay of production but in curtailment of production, and should be referred to as a loss in tons of iron or in units of monetary value and not as a delay in units of time. The same reasoning does not necessarily apply in departments using the product from a blast furnace.

In the case of an open hearth department depending entirely upon iron from the local blast furnaces, a shut-down is not necessarily a curtailment of production. As long as there is storage for the blast furnace production during a shut-down of the open hearth department and there is sufficient open hearth capacity to absorb the stored iron along with the normal output from the blast furnace, the stop could be properly termed a delay in production which would be regained later and would not necessarily represent a monetary loss in so far as production is concerned.

On the other hand, if there is always an abundant supply of iron and a demand for the open hearth product, a halt in operation in the open hearth department would be a curtailment of production and a monetary loss.

Therefore a failure of auxiliary equipment in any department beyond the blast furnace may result in a delay of production or a curtailment of production, dependent upon conditions. But a failure of auxiliary equipment of a blast furnace that causes a reduction of the melting rate is almost invariably a curtailment of production and a monetary loss that cannot be recovered.

Thus it follows that in selecting auxiliary equipment for a blast furnace the feature most desired is reliability. In selecting a skip hoist controller the requirements are in the following order:

1, Reliability; 2, maintenance; 3, depreciation; and 4, initial cost.

RELIABILITY

The detail parts of the controller should be as few as practicable in order to have a minimum number of possible sources of trouble. There should be enough switches to limit the accelerating current to a value that will not be harmful to the motor or other parts of the equipment. Four accelerating switches, thus giving five steps of acceleration, are ample.

Main contacts should be self-cleaning to prevent excessive arcing and freezing. Auxiliary contacts should be so designed as to prevent accumulation of insulating particles that may come from the atmosphere, or elsewhere.

Usually there is heavy electrically-driven machinery operating near blast furnaces that causes the line voltage to fluctuate widely, and shunt-wound switches, designed for 230 volts, particularly for skip hoist controllers, should be designed to operate successfully on any voltage between 175 and 260. The complete controller and its wiring should be so designed that a deposit of coke and ore dust that is common in the atmosphere about a blast furnace cannot cause grounds, short circuits, or sneak circuits.

Skip hoist controllers have in many cases been unnecessarily burdened with elaborate and complicated schemes for obtaining smooth, uniform acceleration, and cut-off point confined within very narrow limits. This is sometimes a very desirable accomplishment for a skip hoist controller to have, but the apparatus necessary for the accomplishment introduces complications and chances for trouble that very materially lessen the reliability of the controller, and the necessity for this close regulation should, whenever practicable, be avoided. A skip hoist controller with which the writer is familiar was originally designed with retarding resistance graduated in about 50 steps, which, by means of regulating apparatus, could be varied to keep the motor speed practically constant from no-load to full load (that is, empty car to load of ore or limestone), through the slow-down period, which gave a minimum variation in the stopping point. It was found that a perfectly satisfactory slow-down effect could be obtained with the use of but two steps of retarding resistance. While regulation is not as close as with the original scheme, it answers all requirements and is very much more simple and reliable.

Since operating a skip hoist is only one of numerous duties devolving upon one man, it is essential that the controller, after being started, perform all of its functions accurately, accelerating, retarding, and stopping automatically. All reasonable protection should be provided, including overload, no-voltage, open shunt field, slack cable cut-out, over-speed, over-travel, and provision to cut off power and apply the mechanical brake in case of failure to complete the circuit through the armature and slow-down resistance.

RESISTORS

The resistor to be used with a skip hoist controller is seldom given sufficient consideration, and for this reason it is very often a greater source of trouble than the controller, and invariably gives more trouble than it should. As the resistor has equal responsibility with the controller proper, and one is useless without the other, they should be given equal consideration. It is important that the resistor have sufficient carrying capacity to limit the temperature rise to 100 deg. cent. High temperatures will in time deteriorate any insulation now known to the art, and the result will be an ultimate breakdown.

Alternate heating and cooling of the resistor result in loose connections, fatigued material, oxidation, broken grids, open circuits, short circuits, grounds, etc. The more frequent the alternations and the wider the temperature range, the sooner will come one or the other of the above-mentioned failures. Cast iron is not a desirable material for resistors because of its fragility. Mica is not a desirable insulation for resistors because of its mechanical weakness and rapid deterioration under certain conditions, such as heat, moisture, etc.

Another weakness in banks of cast grid resistors and one that gives more trouble than any other is the multitudinous number of joints, each grid being afflicted with from two or four joints, one on either side of the lugs.

WIRING

Too much emphasis cannot be placed on the importance of using the best materials and first-class workmanship in installing the secondary wiring of the controller itself, and from the controller to the master switch, etc., particularly in connection with a skip hoist controller. For 250-volt work, wire made for 1500-volt working pressure should be used. Secondary wiring should be extra flexible and no wire smaller than No. 12 should be used. Care should be taken not to run wires connected to high-resistance relay coils in the same conduit with wires subjected to high induced voltages, which may cause improper action of the relays.

MAINTENANCE AND DEPRECIATION

All parts that are subject to renewal should be easily accessible for inspection, repairs, and renewals. Spare parts should be as few as possible. This can be done by making all magnetic switches, all secondary contacts, etc., duplicates of each other. The terminals of all main and secondary wiring should be plainly marked and be arranged so as to simplifyt racing or testing in case of trouble.

A controller that is reliable and easily repaired and maintained will not be subject to depreciation; its life will be determined by obsolescence brought about by changed conditions. Unless there is a change in the design of the blast furnace or skip or some condition arises that renders the controller useless, it will give the same satisfactory service indefinitely.

COST

In selecting a controller for a blast furnace skip hoist, the purchase price should be the last consideration. A controller that would not be dependable seven days in every week should not be accepted as a gift, if one more dependable could be obtained.

HIGH-SPEED COAL HOIST

An outline diagram of a high-speed hoist, the control equipment of which will be considered, is shown in Fig. 4. This is a double hoist, each being capable of hoisting 100 tons of coal per hour, with a grab bucket of 70 cubic feet capacity, weighing 6200 pounds empty. The average weight of coal per lift is 1¼ tons, making a total average load of about 9000 pounds. Each hoist is driven by a 300-h.p., continuous rating, compound-wound 500-rev. per min., 230-volt, d-c. motor, which is geared to a drum on which is the closing cable. To this drum through a solenoid-operated friction clutch is connected the shell cable drum.

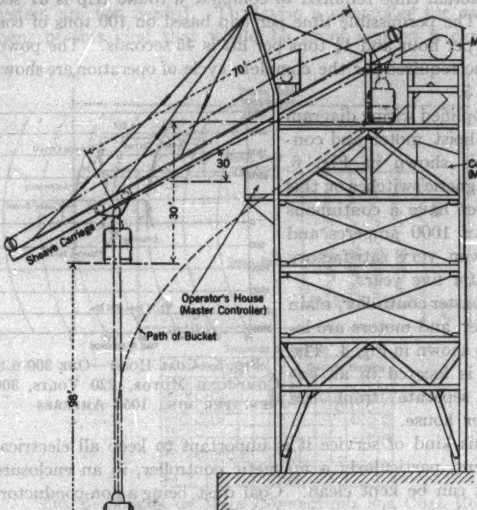

Motor House
70'
30
30'
Control House (Main Controller)
Sheave Carriage
Operator's House (Master Controller)
Path of Bucket
98'

FIG. 4—COAL HOIST

The solenoid which operates the friction clutch is controlled by a push-button switch in the handle of the operator's master controller. After the bucket is closed and the stress on cables is equalized, the friction clutch operates, connecting shell and closing cable drums together. While the bucket is being hoisted, the sheave carriage is moved by an auxiliary drive up an incline, the path of the bucket describing a parabolic curve, the total vertical lift being 128 feet.

When the bucket reaches the dumping point the friction clutch is released, a band brake, operated by foot lever, is applied to the shell drum, power is applied to the motor and closing cable drum in the reverse direction, and the coal is dumped into a chute and the bucket continues lowering and moving down the incline at the same time. The hoist motor is retarded by dynamic braking, with the shell and closing cable drums locked together and the bucket in the open position.

The actual time required to complete a round trip is 37 seconds. The permissible time per trip based on 100 tons of coal hoisted per hour and 1¼ tons per lift is 45 seconds. The power and time required for the complete cycle of operation are shown in Fig. 5.

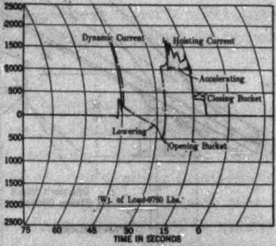


FIG. 5—COAL HOIST—ONE 300-H.P. COMPOUND MOTOR, 220 VOLTS, 300 REV. PER MIN., 1050 AMPERES

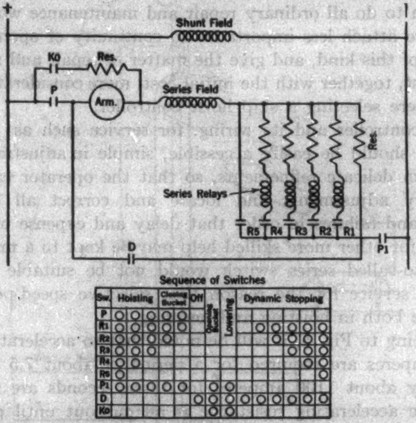
A simplified wiring diagram of the hoist motor and controller is shown in Fig. 6. The magnetic switches on this controller have a continuous rating of 1000 amperes and have given very satisfactory service for five years.

The master controller, main controller, and motors are located as shown in Fig. 4. The resistor is located in an enclosure separate from the controller house.

On this kind of service it is important to keep all electrical equipment, particularly a magnetic controller, in an enclosure where it can be kept clean. Coal dust, being a non-conductor, will only be troublesome due to lodging on secondary contacts and insulating them, and by getting into moving parts of magnetic control apparatus; aside from this, it will do no particular damage except that precaution should be taken to prevent coal dust from accumulating in enclosures in which there is electrical apparatus, particularly in controller rooms, for the reason that arcing is liable to cause a conflagration of the dust.

Experiments that have been made by the U. S. Bureau of Mines have proved that less than 0.2 oz. of coal dust per cubic foot of air will, under favorable conditions, permit propagation of flame from particle to particle of dust and cause a conflagration that will produce a pressure in an enclosure, which will dislodge any dust that may be accumulated on the frame work of the enclosure, etc., and may cause an explosion with disastrous results. This feature should be kept in mind when installing electrical equipment of any kind about a coal hoisting or crushing plant.

Since an equipment of this kind requires an operator having at least the intellectual capacity of a street car motorman, elaborate protective features in connection with the control system are not needed. To devise a controller for an equipment of this kind that would be proof against a careless or incompetent operator would be impracticable if not impossible. The only protection necessary, as has been proved by five years' operation, is current-limit acceleration and overload protection.



Sequence of Switches

Sw.	Hoisting			Closing Bucket		Off	Opening Bucket	Lowering	Dynamic Stopping					
P	○	○	○	○	○									
R1	○	○	○	○	○					○	○	○	○	○
R2	○	○	○	○							○	○	○	○
R3	○	○	○									○	○	○
R4	○	○											○	○
R5	○													○
P1	○	○	○	○	○		○	○						
D						○	○	○	○	○	○	○	○	○
Ko							○	○						

FIG. 6—SCHEME OF MAIN CONNECTIONS FOR COAL HOIST

As stated, there are two duplicate equipments on a common structure operating as one unit, hoisting coal from the same boat. To provide against heavy current surges on the transmission line and power plant, the hoist controllers were interlocked electrically to prevent both hoisting at the same time, but allowing one to hoist while the other is lowering. In addition to the benefits that were expected, this arrangement has resulted in lower maintenance cost on the hoisting plant, brought about by more even stresses on the structure, and a more even pace on the part of the operators, there being less tendency to reckless operation, since one operator cannot hurry unless the other operator does likewise, and one cannot slow down without affecting the other. The result is that capacity is maintained while stresses on the hoisting equipment and structure, transmission lines and power plant, are much less severe. This arrangement also permits of a more efficient use of the transmission copper.

Since an equipment of this kind must necessarily have some reserve capacity, there is usually sufficient time during the working turn to do all ordinary repair and maintenance work. We therefore attach less importance to continuity of operation for service of this kind, and give the matter of repair and maintenance cost, together with the initial cost, more consideration than if we were selecting a skip hoist controller.

The controller and its wiring, for service such as just described, should be easily accessible, simple in adjustment, and free from delicate refinements, so that the operator can make necessary adjustments and locate and correct all ordinary defects and failures in order that delay and expense of having to send for other more skilled help may be kept to a minimum.

The so-called series switch would not be suitable for this class of service for the reason that selective speed points are desirable both in hoisting and lowering.

Referring to Fig. 5, it will be noted that to accelerate, about 1400 amperes are required for a period of about 7.5 seconds, and only about 1100 amperes for three seconds are required after the accelerating resistance is all cut out until power is cut off. The accelerating resistance therefore is in circuit about 75 per cent of the total time that the motor is hoisting and it is in circuit about 20 per cent of the total time required for a complete operating cycle.

The accelerating resistance for this work should therefore have a capacity of 1000 amperes continuously with a temperature rise of 100 deg. cent. if it is to give satisfactory service. A resistor so designed would prevent excessive heating in normal operation and prevent burn-out in case of accelerating switches failing to close and leaving part of the resistance in circuit. With this rating, the saving in repairs and maintenance over a period of years would pay a handsome return on the additional investment necessary over what would be required for a resistor that would ordinarily be supplied for starting a 300-h.p. motor at full load on a 35-second operating cycle.

It would be conservative to say that no steel plant is free from trouble and expense incident to accelerating resistance of insufficient current carrying capacity, and that in a great many cases the repair and maintenance cost of the resistor alone, neglecting the expense and interruption to plant operation incident to resistor burn-outs, etc., would justify the expense of replacing the troublesome resistor.

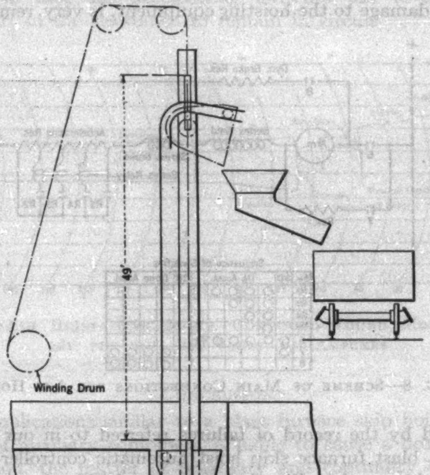


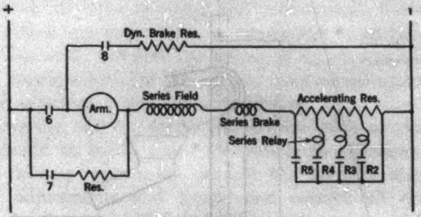
FIG. 7—ASH HOIST

LOW-SPEED AUTOMATIC ASH HOIST

The equipment to be considered here is used for hoisting ashes from a gas producer pit and dumping into a car on an elevated track, the general arrangement of the hoist being shown in Fig. 7.

The controller was designed to be operated by men who wheel ashes from the gas producer, it being only necessary for them to push a button and the bucket of ashes is hoisted and dumped and the bucket returned to the loading position without further attention. A simplified wiring diagram and sequence of switches are given in Fig. 8.

Without the automatic controller the man who would operate the hoist would have to be more skilled and be paid a higher wage rate than would a man who was only required to wheel ashes. This feature alone would justify the installation of the automatic controller. Then the possibility of an incapable operator damaging the hoisting apparatus is eliminated. The possibility of a properly designed automatic controller failing, and causing damage to the hoisting equipment, is very remote, as is evidenced by the record of failures referred to in our description of a blast furnace skip hoist automatic controller.



Sequence of Switches

Sw.	SD	Up Accel.					Off	Down Accel.			
R2		○	○	○	○						
R3		○	○	○							
R4		○	○								
R5		○									
6	○	○	○	○	○	○					
7	○							○	○	○	○
8								○	○	○	○

FIG. 8—SCHEME OF MAIN CONNECTIONS FOR ASH HOIST

It will be noted in Fig. 9 that nearly double the time is required to lower that is required to hoist the bucket. The reason for this is that five minutes elapse from the time that the full bucket of ashes is started up until the man returns with a barrow of ashes for the next empty bucket. Advantage is taken of this time and the bucket is allowed to return all the way down on very low speed in order to reduce wear and tear on the apparatus and simplify the control.

The requirements of a controller for this service would be about similar to those of a blast furnace skip hoist controller in that it should have every protection to avoid damage to the hoisting equipment and that it should function positively and accurately. These features, together with maintenance and initial cost should be given most consideration. Continuity of operation, although desirable, is not absolutely essential as is the case with a blast furnace skip hoist controller.

A controller for this service should be enclosed to prevent its being tampered with. All repairs and adjustments should be made by a competent electrical repairman.

The accelerating resistance should carry full load current continuously with normal temperature rise, to avoid excessive heating in case the accelerating switches fail to close and allow part of the resistance to remain in circuit.

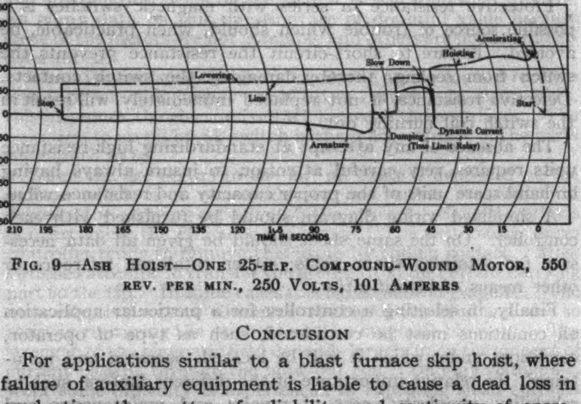


Fig. 9—Ash Hoist—One 25-h.p. Compound-Wound Motor, 550 rev. per min., 250 Volts, 101 Amperes

Conclusion

For applications similar to a blast furnace skip hoist, where failure of auxiliary equipment is liable to cause a dead loss in production, the matter of reliability and continuity of operation is a necessity, in relation to which all other requirements are of secondary importance. The initial cost of a controller for this service should be a last consideration.

Where conditions are similar to those of the high-speed coal hoist that we have considered, where an ordinary delay does not affect plant operation and where the operator, since he must be skilled to a certain degree to operate the equipment, could also take care of all ordinary repairs and maintenance of the electrical equipment, the question of simplicity, repairs and maintenance and initial cost should be given most consideration: the matter of continuity of operation, while desirable, is not a first consideration.

Applications similar to the low-speed ash hoist which has been considered, which are to be operated by unskilled labor, require that the controller perform its functions positively and accurately, and have all protective features necessary to avoid damage in all cases to the apparatus which it controls.

Where the controller is designed for automatic acceleration, to provide against accelerating switches failing to close and leaving part of resistance in circuit, and on manually-operated controllers where the accelerating period represents 10 per cent or more of the complete operating cycle, the resistor should have carrying capacity equal to that of its motor with a maximum temperature rise of 50 deg. cent.

Protective resistance in series with magnetic switches is a possible source of trouble which should, when practicable, be avoided. Failure to short-circuit the resistance prevents the switch from sealing, thereby damaging the switch contacts. Defective resistance, if not replaced immediately, will result in the switch coil burning out.

The absence of any attempt at standardizing high-resistance units requires very careful attention to insure always having on hand spare units of the proper capacity and resistance value.

A simplified wiring diagram should be furnished with each controller. On the same sheet should be given all data necessary for obtaining spare parts; either catalogue reference or other means of identification.

Finally, in selecting a controller for a particular application all conditions must be considered, such as type of operator, conditions under which it will be located, operated and maintained, the relative importance of the different factors, such as reliability, simplicity, cost of repairs and maintenance and initial cost, the order of importance of which will be different for different applications.

A careful analysis of all of these factors will help to determine the best controller for the particular application and whether it should be non-automatic, semi-automatic, full automatic, or manually operated.

Generally speaking, manually-operated controllers for service above 25-h.p. capacity should not be used on hoisting equipment.

DISCUSSION ON "CONTROL OF DIRECT-CURRENT HOISTS IN IRON AND STEEL MILLS" (STOLTZ AND LUM), AND "DIRECT-CURRENT CONTROL FOR HOISTING EQUIPMENT IN INDUSTRIAL PLANTS" (SNYDER), PITTSBURGH, PA., APRIL 16, 1915.

H. D. James: The paper by Messrs. Stoltz and Lum brings out the importance of continuity of service.

The theoretical calculations in connection with the arcing of electric switches are difficult owing to the many factors that enter into the problem, yet it is the most important item that has to do with the maintenance of an electric contactor. The mechanical construction of a switch is easily analyzed and passed upon by a good mechanical engineer. The question, however, of the life of contacts, freedom from freezing and wear on arc shields and surrounding parts of the switch is still somewhat obscure. So many data on this question are of doubtful value because some of the factors are not available and others are not accurately determined.

When the arc is ruptured under oil, the arcing contact receives a deposit which is largely made up of carbon. In many cases, this improves the electric contact between these surfaces. The objection to an oil-break switch is the inaccessibility of the parts submerged in oil.

When the arc occurs in the air, an oxide is deposited on the surface which is a non-conductor and unless removed, will decrease the carrying capacity of the contact. Several methods of overcoming the difficulty are in use. The well-known drum controller tends to remove this oxide by sliding contact. Most switches attempt to transfer the arcing from the current-carrying part to the tip. In some cases this tip is made of graphite. The most effective way to eliminate trouble of this kind and also to assist in rupturing the arc is to use the magnetic blow-out. The strength of the magnetic field depends largely upon the amount of current passing through the blow-out coil. On high-voltage a-c. work some difficulty is experienced in rupturing small currents due to the absence of a strong magnetic field. This is partly overcome by providing a horn gap, the arc always tending to rise and extinguish itself on such a gap.

When a contactor switch is closed and the contacts first touch, they tend to bound apart, causing a small arc. Although this arc is not nearly so large as the arc at opening the circuit, it may cause much more damage, as the contacts are immediately closed after the arc, and if any of the metal of the contact becomes fused, the contacts will have a tendency to weld together. This fact is often overlooked.

The tendency to arc at closing is materially reduced by a long rolling action, somewhat in the way two gear teeth mesh. This rolling action easily breaks apart any spots which have a tendency to weld. Unless this rolling action is theoretically correct, which it never is, there will be a slight sliding action sufficient to keep the contact surfaces in good condition. Where the action at closing is largely a sliding one, the rough points on the contact surfaces have a tendency to prevent the sliding, and any spots that weld together require considerable pull on the magnet to separate them. If the surface becomes quite rough, the sliding action will be stopped by the contacts locking together and this will prevent the armature of the magnet from entirely closing. The motion of the contacts upon each other transfers the arc from the part of the contact which carries the current to the tip, which can be burned away without injuring the capacity of the switch. The action of the contacts should be sufficient to allow for considerable burning.

The arrangement of the magnetic blow-out is very important, as the quick rupturing of the arc reduces the burning on the tip. The design of the magnetic field is well understood and can be easily figured. Where a narrow contact is used, a better field can be obtained on small current values, which is one of the limiting features in rupturing the arc.

It is well known that the arc flares against the arc shields, and all designs of blow-out structures make an attempt to keep this arc in the center of the gap. Some designs have been much more successful in this particular than others.

During the last ten years a new form of magnet switch has been introduced, known as the series lockout switch. The operation of this switch is now well understood and need not be amplified here. The principal advantages of such a switch are:

(*a*) The substitution of a series coil for a shunt coil.

(*b*) The elimination of the electrical interlock and current relay. These advantages have often tempted the engineer to use series switches on services for which they are not adapted.

Since the switch is held closed by a series coil, it follows that when the current reaches a predetermined minimum, the switch will drop open. It then requires a certain increase in current value to close the switch again. A sudden drop in the line voltage due to starting another motor may cause a momentary reverse in the current through one of these switches, and open it, so that a switch designed to hold in at even a small current value will not always remain closed. In some cases the series coil is not heavy enough for continuous service and may burn out if the switches fail to close. Designers have attempted to make these switches hold in and also to close at a minimum current. This tends to make the switch delicate in operation and easily affected by vibration. These facts should be borne in mind when series switches are specified. The series switch is a splendid addition to our line of contactors and when applied in the proper way, has materially decreased the complications of contactor control.

W. C. Kennedy: In regard to the above papers, I would like to refer in particular to the blast furnace skip hoist controllers, as that seems to be one of the most important points under discussion.

The point brought out in Mr. Snyder's paper, that the blast furnace hoist should be so designed that a very accurate stop is not essential, is a good one. Some types of furnaces designed several years ago were often of such a construction that, in order to obtain the proper slow-down speeds and accurate stopping positions, the controller must necessarily be very complicated. This point refers in particular to equipments in which the skip bucket was suspended in such a manner that, if the slow-down speed was made very rapidly, the bucket would start to swing and it then became impossible to obtain an accurate stopping position. Fortunately in all recent furnace applications, construction has been modified to such an extent that the control problems are very much simpler.

In connection with blast furnace practise, undoubtedly the most essential thing is continuity of operation and this means safety, not only in the controller but also in the motor equipment. It is, therefore, important to have the proper safety features incorporated in the automatic controller, such that a positive operation of the slow-down and stopping mechanisms is insured. Due to the fact that the load conditions vary so widely on blast furnace equipments, some means for automatically varying the armature shunt resistance, as brought out in Mr. Snyder's paper, is imperative in most cases and this feature should be such that the resistance would vary according to the load on the skip.

Messrs. Stoltz and Lum state: "This shunt resistance causes a definite current to flow through the starting resistance and the series field of the motor." I presume that, in that type of slow-down, the current drawn from the line during the slow-down period is practically independent of the load. In order to get an accurate stop, therefore, under all conditions, I believe the slow-down current would have to be excessive, as it practically amounts to impressing a low voltage on the motor armature terminals and obtaining a low speed, which is practically constant regardless of the load on the motor. This means a large current consumption, but, on the other hand, by providing an automatic means for varying this resistance, it is possible to reduce the current consumption during the slow-down period and moreover obtain more accurate slow-down and stopping conditions.

There is another point which is very desirable for skip hoist control: that is, some absolute means of shutting off power in case the slow-down switches fail to operate at the right period. For example, with a skip running approximately 400 ft. per min., depending upon the conditions, in order to make an accurate stop possible, the speed must be reduced to approximately 10 or 25 per cent of its normal value. With such a large speed reduction, it is easily seen that it is absolutely essential that the slow-down feature be certain to work, or else power should be immediately shut off from the motor before the skip approached its final limit.

There are two different ways of accomplishing this. One of the best is the installation of an over-speed governor or similar device. This governor is preferably of the centrifugal type and should be so designed that it will be capable of standing a normally high speed at hoisting and should be sensitive at the lower slow-down speeds.

Another limiting device that has been installed for a number of years is known as the contingent limit. This feature is usually designed to operate so that, if any of the functions fail to take place during the proper slow-down period, all power is immediately shut off from the hoist and brakes applied.

In regard to the question of temperature rise of resistance mentioned in Mr. Snyder's paper, this brings up not only the question of the resistance material itself, but also the method of installation. It is absolutely essential that all resistance be installed so that a free circulation of air is obtained. In many cases the writer has seen resistance break down completely which was of ample capacity and would have been entirely satisfactory had the proper ventilation been obtained. Therefore, the specifications for resistance should not only cover the resistance material alone, but also should pay particular attention to its proper installation.

E. H. Martindale: Mr. Snyder in his paper stated that cast iron was not desirable for grids, because of its liability to breakage. We can probably find objections to almost anything. I wonder whether cast iron, everything considered, is not the best thing to use. He stated also that mica was not satisfactory for insulation purposes, because of its liability to failure, due to moisture, oil and other things. I think the author of the paper, in criticising the construction of the grids, should make some positive recommendation as to something better. We might state, for instance, that individual motor drive is unsatisfactory, because it takes more wire, but we believe it is better than line drive, and if the cast-iron grid and mica insulation is not better than something else, then I think he should state what would be a better substance. He also in speaking of the grids mentioned the millivolt drop between joints, stating it was from 1 millivolt to 6 millivolts in tests which he had made, and called that a 600 per cent variation. I think it should be taken as the percentage of the resistance of the grid and not in percentage of the joint. For example, the machine that he considers carries 634 amperes fully loaded, and the resistance of the grid runs from 0.01 of an ohm to 0.08 of an ohm. With 634 amperes the 6-millivolt drop in the joint is only from 0.1 of one per cent to 0.01 of one per cent of the resistance in the grid. The resistance in cast-iron grids themselves varies as much as 10 per cent, and 0.1 of one per cent would hardly be comparable.

He also speaks about the bucket of the hoist going down about half as rapidly as it rises, and states that this saves wear and tear on the equipment. I am wondering why it would not be advisable to slow down the hoisting and speed up the return a little, to make them about even. That would permit the use of a smaller motor and also reduce the wear and tear on the hoist. Instead of having a hoist which is as rapid as the design, why not even use a smaller equipment, which would reduce the load slightly on the power house?

J. H. Albrecht: I was very much interested in Mr. Snyder's discussion of the means he employed for operating the variable slow-down on the light and heavy loads. He said he had a maximum over-travel allowable of 28 inches. It has been my misfortune to encounter the older types of furnace where the operating men told me that an over-travel of 8 in. would be apt to cause the bucket to go into the bumpers and tear the bicycle wheels from the furnace top. 28 in. is a very good margin but when you get down to a clearance of 6 to 8 inches the stop must be very accurate. We have tried and abandoned the scheme of the accelerator-generator attached to the motor shaft. That is a very delicate arrangement. Under this plan the set-up switch must work on a small voltage variation, especially in the newer types of motors where the speed regulation is very good. In such cases the set-up relay must work on a voltage variation of 10 per cent. Any one familiar with relay design will realize that it is extremely difficult to make a relay work accurately and reliably on a variation of 10 per cent in voltage.

There is another scheme that we tried which is simple in theory but does not work out in practise. We tried using a lock-out switch for varying the slow-down resistance, the coil of this switch being in series with the main line. The idea was that on light load the switch would come in, short-circuit some of the slow-down resistance and give the severe slow-down which is necessary to stop the fast-traveling light bucket. On heavy load, the line current would be high and the switch would remain out and thus give a more gradual slow-down. This scheme is all right in theory, but Mr. Snyder's ammeter curve shows a very marked kick and line current following the application of the slow-down switch. It has been our experience that the kick is much more pronounced than is shown on Mr. Snyder's ammeter record, and that the current will kick practically to zero, depending of course on the speed of the motor. On the light load where it is most essential that the switch should operate the kick is most pronounced, due to the high armature speed. It is very evident that this fact will knock the operation of the lock-out switch or any similar device depending on armature current. It might possibly be made to operate by a very delicate adjustment but would not be accurate or reliable.

After trying these schemes we went back to basic principles and succeeded in getting an accurate stop under all load conditions by a simple adjustment of the slow-down switches. We applied the first slow-down switch a little further out of the " hole " and allowed a sufficient interval between that point and the point of application of the second slow-down to allow the motor to reach a constant speed under all load conditions. We then set the second slow-down at a point about 15 inches from the end of travel or after the skip-bucket had started over the " knuckle." The second slow-down was very severe, being practically a short circuit on the armature. With this setting we were able to get a stop which did not vary more than one inch from a light bucket to a bucket carrying 9000 lb. of ore.

As to Mr. Kennedy's question concerning the height of the current during the slow-down period, we limited the line current on the slow-down to 650 amperes which is slightly over 150 per cent full load on the motor. There is another point which Mr. Kennedy brought up, and that is the question of " protection in case of failure of voltage ". In the case of a balanced hoist where the down-bucket is going up with a coke load and the up-bucket is coming down after having discharged an ore load, you may often encounter the condition where possibly half of the ore load has frozen or stuck in the descending bucket. If the line breaker should blow, the heavy descending bucket will cause the motor to reach the dangerous speed, and the magnet switches on the control board will hold in on counter e.m.f. of the motor. To guard against such condition the only satisfactory device we have at present is a mechanical over-speed device attached to either the motor or drum shaft. This device is not entirely satisfactory as the motor must reach a considerable speed before it will operate, and if the breaker should blow when the cars are about 15 ft. from a limit of travel it would not operate in time to prevent a smash-up.

Paul Caldwell: At yesterday's session there were some general remarks on features which enter into crane hoist operation and also trolley operation. Nothing was said of the bridge motion, which I think presents some problems which are peculiar to itself, and different from either the trolley or hoist motion.

When the new series type contactor was put on the market there was a strong tendency to apply it to the operation of the bridge motion of cranes with only one running speed point in either direction. This was the case, not only with small industrial cranes but with larger gantries and with ore bridges. After some experience with this form of control, several problems have come up which limit such application and in some cases eliminate it entirely.

First, the question of speed of the bridge is a factor of prime importance. In my opinion, a series contactor type controller with one running speed point will satisfactorily operate a bridge provided the ultimate speed does not exceed 50 or 75 ft. per min. Where the bridge is geared to run as high as 200 ft. per min., the rate of acceleration with only one speed point is apt to be too great and cause the wheels to slip, especially if the track is wet and oily. For speeds up to 200 ft. per min. a two-speed point controller would be advisable as it would permit the wheels to grip the track before being finally accelerated to full speed.

For speeds above 200 ft. per min. it would be advisable to use from three to six selective speed points, the number depending on external conditions as well as ultimate running speed.

Second, there is another important factor which requires consideration both for indoor and outdoor cranes, and that is the question of dragging loads. It frequently happens that cranes will be utilized for pulling or dragging heavy loads or cars from place to place, and this work usually falls on the bridge motion.

A common example of this on outdoor cranes is the "spotting" of railroad cars for the purpose of loading or unloading pigs or billets, and it is not unusual to see a crane drag five or six loaded cars in this manner.

This same condition arises indoors in connection with open-hearth charging machines, where the bridge motion is always used to spot the cars in front of the charging doors.

It is unreasonable to expect a controller designed with one-speed point control to handle satisfactorily the operation of the bridge motion of such cranes where the imposed load will vary over so wide a range.

Third, the question of swinging loads on cranes is another point which should receive consideration, particularly where the loads are heavy and the lift a high one. It is difficult, if not impossible, for an operator to handle successfully a hot metal crane, for example, with a single speed point control. A controller with several speed points is much preferred.

In connection with outdoor cranes, there are three elements which enter into bridge operation that make series contactor type control undesirable. First, the condition of the rails; in rainy weather they become slippery and the tractive effort is of course not as great as in good weather, when the rails are dry. An adjustment of the contactors which would be satisfactory for good fast operation, under latter conditions, would cause slippage of the wheels under the former. This can only be overcome by employing two or more speed points which will permit of a slower acceleration when required without a constant change in the adjustment of the control panel.

Second, windage is a factor which seriously affects the operation of outdoor cranes, particularly if the crane is of the gantry type, as on ore bridges. A strong wind blowing directly against the crane will cause the series contactors to lock out and as a result the motor would never accelerate but run at a very low speed on resistance. When attempting to move in the reverse direction, with the wind, the motor would accelerate so fast that the wheels would either slip on the track or the resultant overload due to such fast acceleration would blow the breaker. These difficulties can be overcome by using a controller with two or more points of speed control, and making the adjustments to meet the worst condition.

Third, another point which infrequently occurs is a slight grade in the track or run-way. A crane run-way put on a soft ground level is apt to settle a little at one end, which would produce the same effect as windage and cause the crane to accelerate slowly in one direction and fast in the other. This can be overcome also by use of additional speed points.

In fact, most, if not all, of the difficulties in bridge operation can be overcome by using controllers having not less than two speed control points. The additional number of such speed points would, of course, depend upon the existing conditions to be met and each case would require individual consideration.

R. A. Black: We have no hoists, except those we use on our cranes, and the question Mr. Caldwell has brought out about the bridge motion of cranes is one that requires, I think, a great deal of consideration. That is the type of crane which sometimes gives us trouble in starting with a one-point acceleration. The bridge is so long that if there is a little dampness or grease or anything of a slippery nature on the rails, the crane will tend to start one end ahead of the other and cause considerable trouble, sometimes even to the breaking of gears. I think two or more points of acceleration is a very good thing, and should be applied to cranes, especially for outdoor service.

The question of the series switch acceleration on hoists is a thing which has given us some trouble, especially in the building of the hoists—not so much after the plant is in operation. For instance, the operating department of a plant has installed a 40-ton crane for a certain class of work out of doors, where it is required to lift shafts. We have one case where we lifted an 80-ton shaft with a 40-ton crane, which, of course, is 100 per cent overload. The automatic control in that case gave us some trouble. It was necessary for us to send a man up to short-circuit the relays. If the plant in which the cranes are to be used would buy motors large enough for the work they have to do, then the control would be perfectly satisfactory; but they do not always do that, so that something in the way of standardization along that line would probably help out considerably on control problems. In that case the different speed points would be of value, so that you could throw on a second or third notch and cut out more resistance in order to get your heavy loads started.

The question of resistance that Mr. Snyder brought out is quite important, but one of the principal things is to get the resistance properly located. We often put resistances in places where they are very much exposed. A good deal of dirt accumulates on them and consequently we get into a lot of trouble from heating and the burning up of the grids and other parts. The type of grid is very important; also that we get a grid which can easily be replaced. For that reason, I believe that the semi-enclosed eye is better than the eye wholly enclosed, because it is so much easier to remove the grid and replace it.

Mr. Snyder brought up the question of the acceptability of mica. As a means of insulating I do not know anything better that we could use. No doubt we have a good deal of trouble in replacing our grids from the fact that the mica insulation tears and gives trouble in other ways. I have tried asbestos and other forms of insulation, but have not been able to find anything better than mica. A little care in locating as well as properly arranging your points of distance so that they will not heat will be a considerable help. The conditions of hoisting vary so much that it is really hard to make any general rule. Theoretically you can work out the proposition very nicely, but when the man in the mill says he must get a certain operation, regardless of conditions or effect on the electrical apparatus, you as the electrical man must sit up and take notice. The electrical man under those conditions must get the work out regardless of the wear and tear on the apparatus.

J. W. Welsh: I would like to make the suggestion that perhaps the great multiplicity of automatic and protective devices which the more modern systems of control involve needs to be supplemented by something more simple. For example, we have recently installed an automatic electric control on the Castle Shannon incline of the Pittsburgh Railways Company, on the south side. Work of this character requires a very close stop, perhaps within an inch. This control is very elaborate in its protective devices. It is, in the first place, of course, of the remote type. There is an auxiliary generator supplying the voltage dependent upon the speed of operation, and the difference between the voltage of this generator which is separately excited from the main line and the line voltage is used to operate the relays which actuate the accelerating switches and retarding switches. In addition to this, there are, of course, the relays themselves as an additional link in the chain. There are on the main drum of the incline stop-motion switches operating through a screw, which at the end of the travel will start the retarding process. There is an over-speed device in connection with the main drum of the incline, and in these various ways the incline would be brought to rest by automatic and safety devices. There is also a " dead man's " handle on the main controller, so that in case it is released the retarding process will be brought into play.

The point I want to bring out is that all of these safety, protective and automatic devices which have a very useful function, offer just that many additional links in the chain and that many additional opportunities for failure. Before this system was introduced, everything was manual, and, of course, everything depended on the operator.

In this case the continuity of service is absolutely a primary requisite, and I would like to make the suggestion, that perhaps there should be some simple throw-over device whereby all of these automatic devices by one throw of a switch could be cut out, and a simple manual resistance type of control substituted. Any system of remote control also has to bear the additional expense of maintenance, that is, the maintenance of these additional devices. It seems to me there is a balance between the cost of this additional maintenance and the cost of repairs of the straight manual device, where you do not have the advantage of the automatic features.

John D. Wright: Regarding the allowable temperature rise on grids, of which Mr. Snyder spoke, I think he is rather too conservative in limiting it to 100 deg. cent. Since 600 deg. cent. is about dull red heat I believe 200 deg. rise would not be at all objectionable.

I would like to learn if Mr. Snyder has any substitute for cast iron for grids.

Mr. Snyder states that " Protective resistance in series with magnetic switches is a possible source of trouble, which should, when practicable, be avoided ". I think almost every one agrees with him in that respect.

Then he says, " The absence of any attempt at standardizing high-resistance units requires very careful attention to insure always having on hand spare units of the proper capacity and resistance value". I believe there are in the market resistance units from 0.1 of an ohm to 10,000 ohms that are standardized.

Another subject that was not brought up in connection with automatic hoist control is that of limit switches. I would be interested to hear what type of limit switch Mr. Snyder used on his ash hoist. Was it a drum type geared or direct-connected to the hoist drum, or a track type operated by movement of the skip?

T. E. Tynes: It has been my experience that the continuous duty coil is far better than to complicate your mechanism by any external resistance coils in series with your operating coils for intermittent duty. The number of applications where you require a quick snappy action and use a lower voltage coil in order to get that action, are so few compared with the operations where you could use a standard coil, I do not believe we are justified in complicating our control equipment by adding these various resistance coils in series with the operating coil. In fact, we have cut them out entirely where we can, and get along very well. I think the automatic control should be as simple as possible to do the work, and in all cases we have been able to get along with our standard continuous-duty coil.

In regard to grids, our experience has led us to believe that the closed eye grid is the best grid to use. We can build a resistance grid unit that will stand up, and have some in service now which have been in service four or five years. The drop across the joint is just as small as the day they were put in, and we have had no occasion to change any section of the grid. A very much larger area of contact between the sections of the grid is obtained by having the solid eye rather than the U type eye. In some of the earlier resistances there were failures in between the sections of grids, and on some of these grids we found as high as 40 per cent of the total ohmic drop through the grid was in the joint. By cutting out the failures and making the eye solid, and putting them eye to eye, and of large area of contact, we cut down that joint resistance and cut out all trouble. The resistance is where it ought to be, that is, in the material of the grid rather than in the connection.

Paul Caldwell: I was interested in Mr. Welsh's remarks regarding the electrification of the Castle Shannon incline, in the city of Pittsburgh. Mr. Welsh mentions the complexity of the control required and its excessive up-keep, and makes some claim for manual control as being more practical for the work.

I know of one incline installed in the city of Johnstown, Pa., which is operated by an a-c. motor from a power source of 2200 volts three-phase, 25 cycles. The control for this motor is very simple, consisting of two oil-immersed primary reversing contactors, sufficient accelerating contactors and two current limit accelerating relays. The equipment has been in operation for a period of two and one-half years and never had a single failure. The cost of up-keep on the controller, outside of oil used for the primary switches, would probably not exceed $5 a year.

This equipment was made to successfully accelerate the incline under the widest variations of load, without requiring any changes in the adjustments of the controller after its first installation.

I cannot agree with Mr. Welsh that the installation of magnetic control is more expensive than manual from the standpoint of maintenance, or that it is more intricate to operate. In many cases it is more expensive to install but this item is nearly always offset by the resultant saving in up-keep.

C. S. Dauler: I agree with Mr. Caldwell on bridge control for some types of bridges. If the one- or two-point series switch controller is not satisfactory for bridge travel, on account of switches locking out and preventing operation or acceleration when the bridge is called upon to handle loads that are unfair and in excess of the work for which the bridge was designed, why will a selective speed controller with series relays and shunt switches be any improvement? The series relay will, of course, lock out and prevent closure of accelerators and fail to cut out the accelerating resistance the same as the series switch, if the series relays are set at the same closing value as the series switches in order to give the motor the same protection.

J. A. Albrecht: I agree with the last speaker in regard to the objection to the series switch on the point of starting heavy loads when it is adjusted for light loads. This objection is inherent in any system of current limit control. If the series switch will not accelerate, the relay acting on the shunt switch will not. If load conditions vary widely, we must come to a time limit device. There is no other way. You cannot make a current-limiting device work. I have met this condition often in mine work. With wide fluctuations in voltage and load, you cannot do any better than to put a dash-pot time-limiting device of some sort on the apparatus, as the current limit will not work under those conditions.

C. S. Dauler: I would also add that I believe it was Mr. Black who brought up the point that the crane is often called upon to handle loads on the hoist greatly in excess of what the crane was designed for. I have a case in mind where a 75-ton crane, magnetic switch, dynamic brake controller was tried out. The first load hooked on the crane was the bed plate of a mill engine, weighing 122 tons. The crane was 75-ton capacity, 75-h.p. motor on the hoist, and the relays on this controller were set for handling a 75-ton load. This 122-ton test load was handled and juggled around and raised and lowered rapidly without any adjustment whatever of the relays.

Paul Caldwell: I do not think that the point I was trying to bring out was correctly caught by either of you gentlemen. What I was trying to say was this—That where we have a condition of wet track, as in outdoor crane operation, the controller with only one speed point will accelerate so fast as to cause the crane wheels to slip, assuming of course that the contactor adjustments are not changed from normal operation. By introducing a second or low-speed point in the controller, it can be successfully adjusted to meet the varying conditions, provided the speed is within the limits previously mentioned.

This second or low-speed point is primarily introduced to limit the energy input to a value sufficient to break static friction and put the crane in motion, after which the current limit acceleration will bring it up to full running speed. Under such condition current limit acceleration is just as satisfactory as time limit, or any other automatic method.

I agree with both gentlemen that the current limit effect is equally as satisfactory with series contactors as with shunt contactors and series relays, and if the load is of such value that one will lock out, so will the other.

As regards current limit against time limit acceleration, a current limiting device controls the acceleration of the motor, depending on the armature current, which is a factor in its operation, while a time limiting device is governed by an element entirely independent of the motor.

With the use of current limit acceleration, the relays or series contactors can be adjusted to limit the accelerating peaks to a safe value which will not cause sparking or excessive heating of the coils. The time rate of acceleration with such controller would be automatically governed by the load current and would increase with light loads and decrease with heavy loads. This is exactly what is desired to secure the most efficient acceleration with maximum protection to the motor.

Should a load be imposed on the motor which could not be accelerated with the relays set at maximum safe value, any other means which might be employed to force acceleration would result in serious overloading of the motor and inevitable commutation trouble. This is just what would occur with the application of time limit acceleration which simply acts as a means of forcing acceleration regardless of the load imposed on the motor.

The second point on the controller, as I mentioned before, is added merely to insure the motor starting without slipping the wheels of the crane, after which the current limit feature will successfully bring the motor to its full running speed.

Francis J. Burd: I have noticed that not much has been said on the question of the limiting switches. It seems to me this is an important part of the equipment. I believe a limiting switch should be positively connected mechanically to the winding drum and the contact ought to be made double-pole, and also should be of the air-break type. I speak of the air-break type on account of its being free from the possibility of surface contact being formed, as might occur on the sliding contact type, through particles of metal being worn off the contact by abrasion. These metal particles would in time tend to prolong the opening of the circuit, which would result in the bucket being carried beyond the stopping point. An additional safety limit could be easily provided by the use of over-travel-switches so connected that if they were opened by the equipment moving beyond the safe point, all power would be cut off, putting the hoist out of commission until a competent person could be called to find the cause of the over-travel. This over-travel switch would also act as a check on the brake, as it would tend to call attention to sliding from this source.

Another question is that of the master controller. Mr. Coey spoke yesterday of having a substantial master controller. I agree with Mr. Coey's remarks on this, as I believe a good husky master switch should be used. There is one other point, the question of brakes. I believe the brake on the hoisting equipment should receive very careful attention and should be made large and husky, and of ample heat radiating capacity.

J. S. O'Donovan: There has been a great deal said here from the standpoint of the manufacturer of the apparatus. A number of operating men have spoken. I think that the operating men today are very fortunate. In 1898, Mr. A. E. Maccoun, an electrical engineer, started out to build a blast furnace skip hoist. Mr. E. E. Slick was chief draftsman and Mr. Thomas Morrison was the general superintendent.

Mr. Maccoun had much trouble in convincing the management that the electric motor would work on a skip hoist. It took him some time. Finally Mr. Morrison gave his consent to try the experiment. We tried it on the B furnace. I had the pleasure of building the apparatus to operate this hoist from the ideas as given to me by word of mouth. We built a semi-automatic control, with which Mr. Albrecht, I believe, is familiar—they were working ten years ago.

J. H. Albrecht: They are still working some of them.

J. S. O'Donovan: We had a limit of about eight inches. If we exceeded that limit we broke the I-beams at the top of the hoist. We had the experience of breaking quite a number of these beams, from broken shunt fields and different other causes such as the breaking of the brake band. We did not seem able to overcome any of these things at the time. There were no contactors built, there was no manufacturer who built contactors. We made our own contactors. They are not big, and I think it would be worth the while of every engineer who is building that sort of apparatus today to get an opportunity to see some of the old hoists, to see what we had to contend with.

Much has been said about time limits on the blast furnace hoist control, and some of the speakers seem to confuse the time limit features with the blast furnace control and crane hoist operation. The time limit feature is absolutely essential on blast furnace hoists and is the one thing which will be retained. Nothing is gained by eliminating it. A definite time of hoisting is sufficient to burden the furnace and have plenty of time left for melting. As to the crane time limit feature, we should not consider anything of that kind.

Nothing has been said regarding the overloading of cranes. In the plant where I have charge we have twenty-eight traveling cranes, and we do not allow any man to exceed the capacity of the crane with a lift at any time. If we have a lift and the craneman is suspicious regarding the size he refuses to lift. The electrician in charge of that department is called upon, and if he passes on it we make the lift. The electrical department in our plant has absolute control over all electrical apparatus and the men who operate it. The man on the floor and the people who do the work have nothing to say about such details. For that reason, we are able to have "safety first" better than in any other way.

Mr. Palmer, who attended one of our meetings, asked me the question—How is it that you do not have more accidents in the use of cranes? I said—Mr. Palmer, I cannot answer you that question in full, but I will say this—that one reason is, we employ men who are of equivalent capacity to street car motormen and we also have absolute charge of our cranes in the electrical department. We do not allow side pulls on a crane. It is liable to pull a cable off a drum. We absolutely do not allow it. The craneman has strict orders not to move a crane if a side movement is intended or any pulling sideways is to be done. It is a dangerous thing. If the cable gets off the side of the drum in any way, you cannot guard it to stop it. The cable will be cut and it is not noticed. Later on in making a lift the cable breaks. Some people say—Perhaps you do not work your cranes hard. There are two cranes in one department in which we wear notches in the bottom of both hooks, and we renew them every eight months. That is some work on a crane. We travel our loads over the heads of the men, continually, carrying pipe; and the men never dodge, never think of getting out of the way, and we have never dropped a load. In the last nine years in the operation of the butt welding department—it is a threading department, where a great deal of material is handled by cranes—we have never broken a cable on a crane. We inspect these cranes twice a week, and we replace the cables every six weeks, whether they require replacing or not. That is our regular custom. In that way we get as near perfect safety as it is possible to secure in the operation of cranes.

Paul M. Lincoln: There is one point which has been touched on a number of times, and that is the temperature limit which Mr. Snyder puts on his grids, etc. I believe these are too low; the facts of the matter are they are lower than the temperature limits which the new Standardization Rules of the American Institute of Electrical Engineers put on the copper insulation of electrical machines.

Some recent tests have been made which show that the mica in the generators which were installed at Niagara Falls twenty years ago and have never since been rewound, have been subjected to a temperature, at their full load condition, of something over 200 deg. cent. They have been running at that temperature for about twenty per cent of the time for the last twenty years. If the insulation of generators can stand temperatures of that kind, I do not see any reason for limiting the temperatures which we can allow upon grids, rheostats, and apparatus of that kind.

J. H. Albrecht: The resistors used on the old hoists consisted of sheets of ½ by 5/32-inch steel hoop suspended from supports. This crude resistance is still in operation after about seventeen years of service, and has outlasted many equipments of our modern grids, although at the present time Mr. Friedlaender has no complaint to make on the modern grid resistance in use in his plant.

M. A. Whiting: I think if Mr. Snyder wishes to limit the temperatures on iron grids to anything like as low values as he gives, perhaps what he has in mind is not so much limiting the temperatures to 50 deg. rise, as it is limiting temperatures to something like 100 to 200 deg. rise under several times normal load conditions. It would seem that the result might be attained with less tendency toward the development of trouble if inquiries called for resistances, subject to normal practise in temperature rise, and specified those resistances for different current capacities representing the extreme probable operating conditions. The manufacturers are always glad to sell as many tons of iron grid resistance as they are called upon to supply. The manufacturer in a given case will include in his proposition, if he has no information to the contrary, we will say, five hundred pounds or so of iron grids, where he might possibly have found an excuse for running in and trying to get away with two thousand pounds of grids. There are two reasons from the manufacturer's standpoint. One is that if in his opinion 500 lb. of resistance is satisfactory, he owes it to his customer not to try to run in a lot of unnecessary material at an increased price. The other is that if he does try to put something over and recommends unreasonably heavy and expensive equipment, the manufacturer who is in with a proposition which seems to be trimmed down nearer to what is required, will probably obtain the business. Therefore, in all such cases where extreme resistance capacity must be provided, I think it is well for the purchasing company to specify in detail in the inquiries what they wish to have in the way of resistance capacity in excess of what is commonly accepted as average practise. In that case the various manufacturers will understand the requirements of the purchaser and their propositions will be comparable. Ordinarily, if an inquiry calls for four or five times the amount of resistance material that would be used normally for the work, if the manufacturers' representative does not see the reason for it, he will admit that the customer may have a good reason for specifying it. He will make a proposition on that basis, but will also put in his proposition an alternative corresponding to the ordinary practise, and will expect that both propositions be given consideration on their merits.

I think there is room for a closer understanding on the part of purchasers as to what they are calling for when they put out their specifications on rheostats for use with the various classes of control.

G. E. Stoltz: I think the discussion on the part of the various members shows a rather unanimous opinion that a series lockout switch is hardly applicable to bridge type control, that is, on the average crane. In applying control to the bridge of a crane, or any piece of apparatus, we consider the average conditions and these can be well met. But if we overload the crane, it seems to me it is a matter of bad management or poor organization which we should not take into consideration in designing the control, nor should the control be blamed for any accidents under those circumstances. Probably other apparatus is being saved merely due to the fact that the control will not allow the operator to start up under those conditions.

With regard to the comparative simplicity of manual against different types of magnetic control, the control for an inclined plane, of course, naturally is in a different field from that of steel mill control. The former is a proposition that must have constant attention and requires a skilled operator. Other considerations will take place than merely the satisfactory operation of the apparatus. In mill apparatus, on the other hand, there are panels and motors which get very little attention—probably the only time the inspector sees them is when something happens. Of course, that state of affairs could not be allowed on an inclined plane. The upkeep and repairs of a complicated control, as on an inclined plane, may be very small, but it seems to me we have got to balance the attendance that is given that apparatus against probably the repairs on a more simplified mill control. In the end you will come out about even.

W. T. Snyder: In regard to Mr. Kennedy's remarks in reference to stopping the skip hoist in case of failure of the slow-down resistance, we have an arrangement on our skip hoist which accomplishes that end, by means of a relay in circuit with the armature shunt resistance. In case the circuit is not made the relay operates and cuts off the line current, and allows the application of a series solenoid-operated band brake. It was mentioned that the method of assembling the grids was important. If we can keep down the temperature rise by some new method of assembling the grids, all right.

Mr. Martindale asks us to suggest a material better than iron for resistance grids. It was my purpose to tell the manufacturers of some of the troubles that operating men were having. I said that cast iron is not a desirable material, and I also said that it is probably the best we have today, but I do not believe we should be satisfied with it, because it is not good enough. But we do not have any positive recommendations other than that there should be some material that would be better than cast iron, especially for the smaller sections, so that they could not be so easily broken. I think the same statement applies to mica, which is as good as anything we have, but is not satisfactory. I do not believe we should put up with it, but I am not in a position to tell the manufacturers what material should be used.

In regard to President Lincoln's remarks about mica, it has occurred to me that the mica of twenty years ago was not the mica of today.

Mr. Martindale referred to the millivolt drop which I gave, and compared it to the current-carrying capacity of the resistance. The resistance which I refer to is not a resistance used on the machine which was considered in my paper, it was just a bank of resistance which happened to be lying around and we had it measured up. It was a small bank of resistance designed for a 35-h.p. motor, somewhere around 125 amperes.

Mr. Martindale also made reference to the resistance of the different grids varying as much as 10 per cent. I also made some investigations along that line and picked up a few old grids that happened to be taken out of a resistance bank which had been in service four or five years, and measured the resistance of each grid. The grids had identical marks on them and were supposed to be identical grids, in current capacity and resistance value. They were supposed to have a resistance of 0.036 ohm, and we found they actually had a resistance of 0.054 to 0.079 ohm, which was considerably more than ten per cent. Mr. Martindale may have referred to new resistance, and my remarks referred to resistance which had been in use for several years.

One of the speakers also brought up a point about slow return on the ash hoist which is described in my paper. I was on the point of explaining that when going through my paper. This hoist was an old crane trolley for which we had no use and we put the apparatus to work lifting ashes from the gas producer, leaving the speeds as they were. I do not know that it would be of any advantage to cut down the speed of the hoisting operation in order to get more speed lowering. I think it is easier to control the thing going up than it is to control it going down.

Mr. Albrecht referred to the small kick shown on our ammeter curve in connection with the skip hoist slow-down. The peak shown at the first slow-down point was the accelerating switches opening and inserting the starting resistance in series with the armature.

In regard to Mr. Albrecht's point as to what would happen in case the line voltage goes off, anywhere along the length of travel, this would result in the solenoid-operated band brake applying and the skip would come to rest and it would automatically accelerate when voltage comes back.

In cold weather, if the ore was not dumped out of the car, and one car was coming down half full and the other going up fully loaded, the buffer would take the blow of the car coming down, so it would not add to the blow of the up car when it hit the top.

Mr. Wright referred to the matter of standardizing high-resistance units. I have here a list of resistance units giving their ohmic resistance and current capacity. Here is one unit having a resistance of 550 ohms and 0.37 ampere capacity; another 33 ohms, 0.5 ampere capacity; another 2.6 ohms and 5.4 amperes capacity. It is very probable that these units can only be duplicated as a standard commodity by the manufacturer who supplied them. It would be very desirable if the manufacturers would adopt standard values for these units as far as is practicable. We very often find that there are units of different sizes and capacities on the same control board. They look alike, but unless we have the proper information at hand, we are apt to get mixed up.

I do not believe Mr. Wright got my point correctly about not needing limit switches. I referred to the coal hoist only, in that connection. There are so many other things to watch that I do not believe an over-travel limit was needed on that particular job. We do have over-travel limits on the hoisting crane, skip hoist and ore bridges. The limit switch we have on the ash hoist is a geared limit.

For the information of Mr. Tynes, I would say that the millivolt drop which I gave was across the joints between the grids. The grids had a closed eye, and the drop averaged from 1.1 to 6.5 millivolts.

President Lincoln said our recommendations on temperature rise were low. Resistance working at high temperature, with the present method of assembling resistance banks, gives trouble due to contraction and expansion. This loosens up the connections and the clamping, causing burning and sputtering between the grids, unless they are very closely watched. When the temperatures get high, you have oxidation of the grids, changing the resistance value. Better results are obtained at the lower temperatures.

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ALTERNATING-CURRENT CONTROLLERS FOR STEEL MILLS

BY ARTHUR SIMON

Abstract of Paper

The induction motor with either squirrel cage or wound rotor is practically the only type of alternating-current motor used for general industrial purposes in this country and therefore the author has confined his paper to considerations of the control problems offered by induction machines. The various types of alternating-current controller in use are described and illustrated and the advantages and disadvantages of each type as well as its limiting capacities are discussed. A number of typical examples of installations of alternating-current controllers in mill work and allied industries is described.

THE APPLICATION of electric drive in the steel mill and allied industries is beyond the experimental stage, and there cannot be today any more question regarding the general advisability of using the electric motor. The earlier development, however, made use of the direct-current motor almost exclusively, and alternating-current motors have been introduced into the industry on a larger scale only during the last few years. A great many different types of controllers for alternating-current motors have been developed, but their suitability for all classes of work has scarcely been discussed at any of the meetings of the technical societies dealing with these subjects.

From the standpoint of speed control and torque characteristics, as well as in regard to the ease of control for practically all applications, the direct-current motor has proved almost ideal, and it would have remained alone in the field had not the tremendous expansion of the industry required a more efficient power transmission system than is possible with direct current. After high-voltage alternating current had been introduced for the transmission of energy over larger areas and long distances, it was, of course, considered advisable to use the alternating-current motor direct instead of installing translating devices to obtain direct current for the motor drive.

There are on the market at the present time two principal types of alternating-current motors, which are quite distinct in their characteristics—the commutator type motor and the induction motor. Little need to be said about the commutator type motor, because its practical development has been seriously delayed in this country and with a few exceptions, the lines which have been developed are of small capacity, and, therefore, do not offer any great problems to the designer of controllers. It would seem, however, desirable to the writer that the development of the commutator type motor for industrial purposes should be accelerated in this country, following the lead of Europe, where such commutator type motors are employed on a larger scale and with as much success as can be expected from a new machine.

In this paper we deal with American conditions, and we can restrict our considerations to the controller problems offered by the induction machine. The induction machine is built with either a squirrel-cage or a wound-rotor type of armature. The former may be used for constant-speed work and the latter for either constant or varying speed work, but neither one is adaptable for adjustable speed work.

The squirrel-cage motor, on account of its simplicity, the absence of a collector, and its staunchness, is the most desirable machine for steel mill service. Its disadvantages are usually a low starting torque and a high starting current. It can not therefore, be employed where heavy starting friction has to be overcome, and it is, of course, not suitable for the frequent reversal and acceleration of heavy masses. The slip-ring type motor, on the other hand, does not have these disadvantages, but it requires a collector which is the cause of frequent trouble. On account of the necessity of short-circuiting the armature over the slip-rings, brushes and some external connections, the rotor losses are greater than they are in an equivalent squirrel-cage machine, and the efficiency of the slip-ring motor is therefore somewhat lower. In very large systems, the voltage in the armature is relatively high, in order to reduce the current to a reasonable value, and this leads to insulation troubles on the slip rings.

The question of control must also take into consideration purely commercial points. We must weigh the relative advantages of low first cost, power consumption, labor and attendance and the renewals. The effects of these different points are more or less contradictory to each other, and they therefore have to be weighed carefully before deciding upon a particular type of motor and controller.

All types of controllers may be divided into two classes: hand and automatic controllers. There is no strict dividing line between the two classes, as there are a great many devices in which some functions are performed manually and other functions of the same controller are automatic. We therefore speak of semi-automatic controllers, which take a position halfway between the manual and the automatic devices.

From the standpoint of first cost, the hand controller is usually the cheapest, but, on the other hand, the cost of attendance for its operation, the usually increased power consumption due to improper operation and the cost of renewal, due to unwise handling of the controller, may be more than sufficient to counterbalance the increased cost of a full automatic controller for the same work.

FACE-PLATE TYPE CONTROLLERS

The simplest and earliest type of controllers are of the face-plate type. These controllers are used in connection with squirrel cage motors for the control of resistance in series with the primary circuit, and with slip ring type motors, in which case they are usually arranged to handle only the secondary circuit.

The controller usually is self-contained, with the resistance mounted back of the panel. It is necessary to install a separate switch to handle the primary circuit.

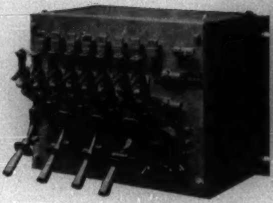
A modification of the face plate type controller which is particularly suitable for large capacities, and which is being built in sizes up to several thousand horse power, is the controller illustrated in Fig. 1. This is the multiple-lever type in which a series of switches similar to those on circuit breakers control the starting resistance. These levers are equipped with laminated-brush main contacts and carbon-to-metal auxiliaries, which are easily renewable, and which handle the arc due to the commutation of the resistance. The great advantage of this controller is that the starting resistance cannot be cut out too suddenly, because the operator has to close one handle after the other, which requires some appreciable time. The controller illustrated is equipped with a no-voltage release, which, is connected in the primary circuit, so that all of the resistance is inserted when the primary switch is opened or when the primary power supply fails. It is advisable to install a no-voltage release primary switch, so that the motor is entirely cut-off the line in case of failure of power. Upon the closure of the primary switch, all resistance is already inserted in the circuit, and the motor may be started up in the usual manner.

The starting of squirrel-cage motors with resistance in the primary circuit is to be recommended only for small machines which start without load. The squirrel-cage motor is usually designed to start with between 1½ and 3 times its normal torque, and a corresponding starting current varying from 7 to 3½ times its normal current. The higher the current, the lower is usually the starting torque. For a given motor this starting torque is proportional to the square of the inrush current or starting voltage, and therefore a comparatively slight decrease of the inrush current by means of resistance will cause a large decrease of the starting torque. Hence this method is not to be recommended where motors have to start frequently and under heavy load.

The face-plate type controller for use in connection with slip-ring motors, on the other hand, is a very satisfactory device if only infrequent starting is required. As with all face-plate type controllers, the limitation of this type lies in the fact that very heavy currents cannot easily be handled on sliding contacts, the multiple-lever type is used where the current to be handled becomes too high. The face-plate type controller may also be used for speed regulation. For larger sizes we would rely also upon the multiple lever type controller.

Fig. 2 shows how the face-plate type speed regulator may be interlocked with overloads and a primary switch so as to permit of starting and stopping from a distance.

It would seem possible to stop the slip-ring type motor by simply opening the secondary circuit, but this is not considered good practise because the closing of the primary circuit of an induction motor with the secondary circuit open may give rise to serious voltage surges which endanger the insulation of the motor windings. Controllers should therefore always be arranged so that the primary circuit is opened for stopping. The opening of the secondary circuit without opening the primary circuit has another disadvantage, namely, that the motor continues to be excited from the primary circuit and there is a great loss of energy due to the iron losses on both the stator and the rotor. The rotor iron losses are higher at standstill than



[SIMON]

FIG. 1—MULTIPLE-LEVER TYPE SECONDARY STARTER WITH NO-VOLTAGE RELEASE

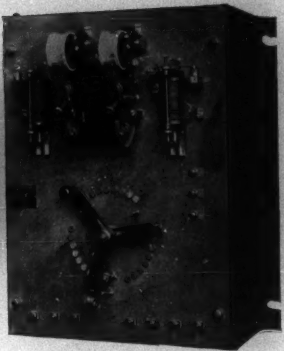


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FIG. 2—SECONDARY FACE PLATE TYPE SPEED REGULATOR WITH PRIMARY SWITCH AND OVERLOAD RELAYS

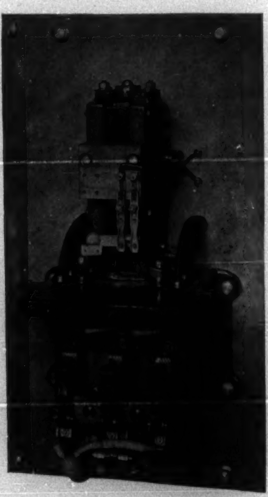

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FIG. 4—SMALL SOLENOID-OPERATED OIL SWITCH WITH TANK REMOVED

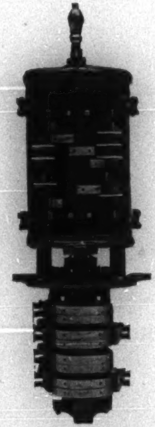

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FIG. 3—ALTERNATING-CURRENT DRUM CONTROLLER WITH PRIMARY OIL SWITCH

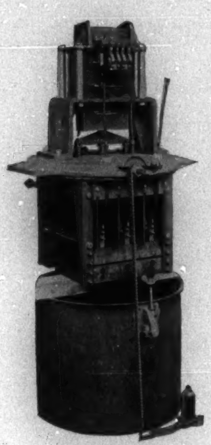

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FIG. 5—LARGE SOLENOID OPERATED OIL SWITCH WITH TANK REMOVED

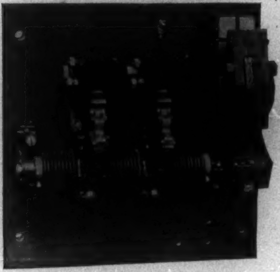

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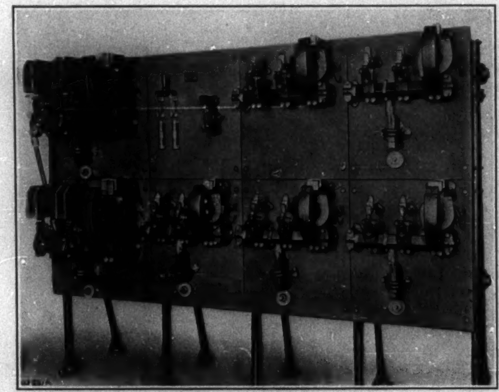
FIG. 6—DOUBLE POLE ALTERNATING-CURRENT CLAPPER SWITCH



[SIMON]

FIG. 7—PANEL WITH ALTERNATING CLAPPER SWITCHES AND SECONDARY SERIES RELAYS

they are when the motor is running at full speed, as the frequency in the rotor at standstill is equal to the primary frequency. Unless the motor is designed very liberally, the lack of ventilation may cause a burn-out, though only the magnetizing current is flowing in the primary circuit.

Where infrequent starting is required, the resistance has sometimes been immersed in oil in order to give a higher starting capacity, although this method has never found a great deal of favor in this country on account of the inconvenience of the oil tank. The only advantage claimed by its advocate is the saving in spacing and cost. The saving in space, however, is only small, and under American manufacturing conditions there is no saving in cost, as the oil tank and increase in weight generally causes an increase in cost which far outweighs the saving in resistance materials. Furthermore, in large capacities, the controller can only be arranged for floor mounting, and in this case, it cannot compare with the open-type starting resistance which permits of a very light and pleasing design, and which can be arranged for mounting in any position.

A face-plate controller of special design is sometimes used for crane work where slip-ring motors have to be reversed frequently. This controller has two fronts, one of which serves as a reversing switch for the primary circuit, while the second, provided with a three-arm lever, controls the secondary circuit of the motor. The controller is equipped with renewable segment and skate-shoe type of contacts. This controller is suitable for smaller capacities of crane motors up to perhaps 50 h.p. Its only disadvantage is that the contacts are exposed and an operator might easily touch them. It has, therefore, been considered preferable in late years to enclose the contacts entirely and so this controller has been replaced more or less by the well known drum-type controller. The general design of this controller is so well known that it hardly needs any comment. The contacts controlling the secondary resistance are arranged so that the latter is cut out in rotation, one step in one phase at a time. The different phases are therefore only balanced on a limited number of points, but this is not objectionable if the stepping in the different phases is arranged so that a minimum of unbalancing is obtained at all times. It has been found that an unbalancing up to 40 per cent in the relative values of the currents in the three rotor phases does not seriously affect the operation of the motor.

Where large amounts of energy are handled in direct-current drum controllers, a blow-out is used to extinguish the arc due to the opening of the circuit. Such blow-outs are not so easily adapted to drum controllers for alternating current and therefore some other means have to be adopted for handling larger currents. The problem has been solved easily by the use of an oil switch, and it is now universal practise to interrupt the circuit of larger motors in oil. For this purpose an oil switch, containing the primary contacts, is usually mounted below that portion of the drum which handles the secondary circuit, or behind the drum. In the first case, the switch is, usually, also of drum construction, the same as the rest of the controller. In the latter case, the switch may be in the nature of an oil circuit breaker construction. The drum controller lends itself not only to the control of motors for intermittent service such as cranes, etc., but also to the speed regulation where the motor runs at a definite fixed speed for the greater length of time. The construction of these speed-regulating drum controllers is the same as those for intermittent service.

Fig. 3 shows a larger size drum controller in which the primary circuit is arranged at the bottom, and is immersed in oil. The oil tank which screws to the top plate of the bottom portion is not shown in the illustration.

When drum controllers are used for intermittent service, such as cranes, and the circuit has to be interrupted frequently, care must be taken in the design of the primary switch, especially if it is immersed in oil. The energy which is dissipated on the interruption of the circuit in the oil must be carried away, as heat, through convection and radiation. If the cooling surfaces of the oil tank are too small, the oil temperature may be raised to a dangerous point which may cause an explosion. This will blow all of the oil out of the tank, and may cause the destruction of the oil switch, or a fire. In order to avoid this, the tank must not only have sufficient oil capacity, but it must also have ample radiating surface.

While touching on the question of oil for breaking the motor circuit, we shall discuss at some length some other questions bearing on the design of oil switches in general for controller work. In the design of oil switches used for circuit breakers the designer usually endeavors to reduce the amount of oil required to a minimum on account of the fire risk. Such circuit breakers operate but very seldom, and therefore the heat storage capacity of the oil and the radiating capacity of the tank are of minor importance. This is different in case of oil switches used for controller work, for they have to operate frequently. In this case, we have to design the switch with ample heat storage and radiating capacity, and a switch which may be very satisfactory as a circuit breaker would not necessarily stand up under controller service conditions, as has been proved by the frequent failures in cases where primary oil circuit breakers have been adopted for drum control for intermittent service without any modification.

Figs. 4 and 5 show respectively a small and a large capacity switch constructed with the above mentioned points in view. It will be noted that the contacts are arranged in such a manner that the arc is formed horizontally and not vertically as in the usual circuit breaker construction. This has proved to be very valuable, as the arc is apparently extinguished more quickly, and therefore the oil is not carbonized as rapidly as with a vertical break.

The switch shown in Fig. 5 has been built in capacities up to 500 amperes at 6600 volts. In an installation where the switch handles a 1000-h.p. three-phase motor, and where it has been installed for five or six years, it controlled this motor circuit some fifty thousand times, and not the slightest amount of carbon has been found in the oil surrounding the contacts, although a good deal of deposit is found at the bottom of the tank. The reason for this is, that with the movement of the contacts as arranged in this switch the oil deposits are not stirred up as violently as they are in the usual oil circuit breaker.

SOLENOID TYPE CONTROLLERS

Drum controllers are now manufactured in capacities up to several hundred horse power, but as the sizes of the motors to be controlled increase, the contact parts become larger and more numerous, and therefore the power to be exerted for operating the drums also increases tremendously. The limiting capacity for the operation of a drum controller is the power which can be exerted without strain by the operator. Another limiting feature in the use of the drum controller is the wearing of the contacts. The contacts at the different points are made and broken slowly, and this necessarily increases the amount of wear due to the arcing, where very large powers have to be handled. The arcing and the resulting wear, is consequently severe.

Where the drum controller is insufficient to handle the required capacity, or where very frequent operation is necessary, and it would tire the operator when handling a large drum, a multiple solenoid type of controller is resorted to. This consists of a number of solenoid-operated, or clapper switches, as illustrated in Fig. 6.

Fig. 7 shows panels with a number of magnet switches mounted thereon. The switches shown in the illustration are suitable only for low-voltage currents, usually up to 550 volts. Where higher voltages have to be handled the solenoid-operated oil switch is by far preferable and is the most universal device. We show, however, in Fig. 8 an air-break switch arranged for 2200 volts, which switch has been used successfully in several instances.

The multiple solenoid controller consists of a number of clapper switches as illustrated. The magnets of the clapper switches are energized from a pilot controller, which, therefore, has only to handle the magnetizing current of the magnets. The pilot controller consists of a small drum or similar device.

The simplest form of the multiple solenoid controller is non-automatic in operation. The energizing of the different clappers, and the speed of cutting out of the resistance is left entirely to the skill of the operator. For large systems this mode of operation is, of course, objectionable because too rapid handling of the master controller will cause excessive current surges on the line, and undue stress on the motor and machinery. Therefore, automatic control is resorted to. This type of controller is the most important to the steel mill engineer. The automatic feature of the controller consists of one or more current-limiting relays, which are connected either to the primary or the secondary circuit of the motor, and which prevent too rapid cutting out of the resistance. The operation of this current-limiting relay is well known, and it has been used on direct-current motors for a good many years. We shall therefore discuss here only those features which distinguish it when used in alternating-current systems.

The largest field for the current relay controllers for alternating-current motors is, of course, the slip-ring type. In this motor the primary circuit is connected direct to the line while resistance is inserted in the secondary circuit and is gradually short circuited, to accelerate the motor to its full speed. Both the primary and secondary current vary with the load and the speed under normal conditions. The secondary current is approximately proportional to the torque exerted by the motor in about the same way as in a shunt-wound direct-current motor. The secondary current becomes zero when the motor runs idle. The primary current, on the other hand, is not a straight-line function of the torque because the primary circuit supplies, besides the load current, the magnetizing current of the motor. This magnetizing current in modern motors is about 30 per cent of the full-load current.

There are today two methods of operating automatic controllers with current-limiting relays; one method is by putting one or several relays in the primary circuit, and the other method by putting the relays in the secondary circuit of the motor.

Fig. 9 shows a relay arranged for connection to the primary circuit. The primary relay requires for a certain range, between maximum and minimum torque, at which the relay is to act, a more accurate adjustment than the secondary relay, because the primary current does not fall off as rapidly as the torque. It has the further disadvantage that it cannot be cut out when it has done its work, except by the addition to the controller of another switch of sufficient capacity to handle the primary circuit. The installation of such a switch is objectionable on account of its cost. The primary relay, therefore, has to be designed for continuous service which makes it rather bulky and sluggish on that account. On the other hand, the secondary relay can be connected so that it is cut out by the same switch which cuts out the secondary starting resistance, and therefore would have to be designed for very intermittent duty only, and would be correspondingly light and sensitive.

Fig. 10 shows a multiple-relay type of controller with relays in the secondary circuit, one relay being employed for each step of resistance, and the different relays are so connected that they always form the star point of the resistance in circuit, and are cut out when the corresponding resistance step is cut out of circuit by the succeeding clapper switch. As the relay itself forms the star point of the resistance, and therefore the potential difference between any two points of the relay is only equal to the drop in the relay coil, it is necessary to insulate these coils only very lightly from each other.

The relay in the secondary circuit has an apparent disadvantage due to the change in frequency of the current in the secondary circuit. When a motor operating on a 25-cycle circuit having a slip of 5 per cent reaches normal speed, the frequency in its secondary circuit is only 1¼ cycles per second. As the relay has, of necessity, very light moving parts, this low frequency would cause it to pump up and down, unless it was

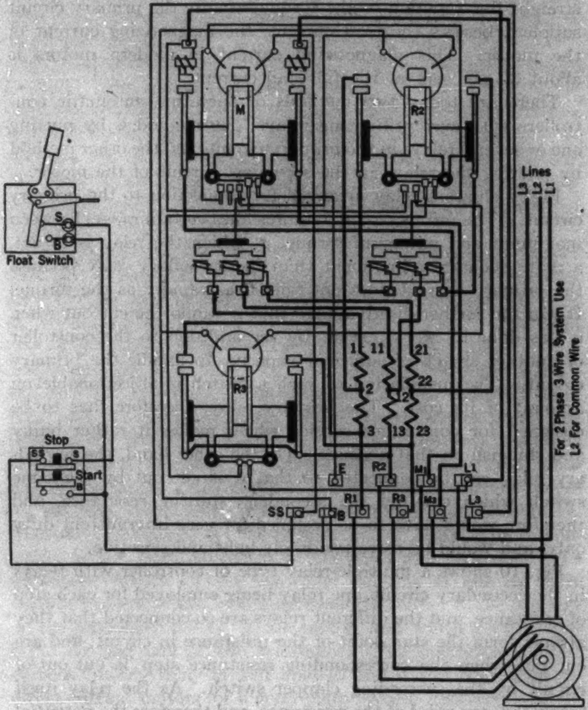

M
R2
R3
Lines
L3 L2 L1
S
B
Float Switch
Stop
SS
S
Start
B
1
11
21
2
22
2
3
13
23
E
R2
M1
L1
R1
R3
M3
L3
SS
B
For 2 Phase 3 Wire System Use
L2 For Common Wire

Fig. 10—Connection Diagram of Series Relay Self-Starter

provided with some means for limiting such pumping, such as a shading coil, which at low frequency is really not very effective. Another way to avoid the pumping is to make use of the fact that the total pull exerted by three equal coils which are connected in the three phases of the secondary circuit is constant as long as the current is balanced and constant. These relays are wound with three coils which are connected together at one end, while the other ends are connected to the respective clappers and resistances. The relay has an absolutely constant pull regardless of the frequency of the secondary circuit. It can therefore be made more sensitive than a relay which is connected to one phase only, and is provided with shading coils or other means to prevent it from chattering. As mentioned above, the use of the shading coil will not really protect against chattering. In order to get a constant pull with this arrangement it will be necessary to have the shading coil flux displaced 90 deg. from the main flux, and to have both of equal magnitude. This result cannot be accomplished, and therefore the relay will have a tendency to chatter as the frequency in the secondary circuit decreases with increasing motor speed. The pull on the plunger of the relay varies therefore between a given minimum and maximum, even with constant effective current flow in the secondary circuit, and when the frequency is low, and the inertia of the plunger which tends to hold it up is relatively small, the relay will drop before the effective current in the secondary circuit is equal to that for which the device is adjusted. Hence such a relay will always work more or less erratically, and at the best it will require a much wider limit of setting than the three-phase relay described above.

It is, of course, not necessary to have the three coils of the secondary relay connected so as to form the neutral point of the resistance. In some cases it is necessary to have the three coils insulated from each other. This is the case where the relay is used as a " jamming " relay, in which case it has to be connected ahead of all of the resistance and directly behind the slip rings of the motor. Where the secondary circuit has a relatively high voltage, and in motors of large capacity, it is, of course, possible to connect the relays to current transformers inserted in the secondary circuit instead of connecting them directly into the latter. This is particularly valuable in case of the " jamming " relay, which otherwise would always have to be insulated for the maximum secondary voltage.

There is still a good deal of discussion as to the advisability of using a single relay controlling several steps of resistance instead of a separate relay for each step. It seems to the writer that the latter method is to be preferred, because it is possible to set the different relays for different currents. This is a particularly valuable feature in machinery such as centrifugal pumps and so on, where the torque required to accelerate the motor varies between the low speed and high speed. Each relay is then set for a different accelerating current, a feature which cannot be obtained with a single relay in the primary or secondary circuit.

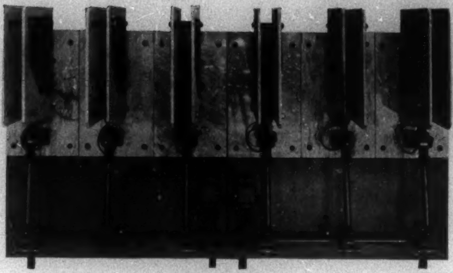
The simplest kind of current relay controller is a non-reversible self-starter for use in connection with machinery which always revolves in the same direction. Instances of this kind are centrifugal pumps, blowers, compressors, and so on. The operation of such machinery represents nothing that is novel in the art, and it therefore need hardly be discussed here. The controller consists of a suitable clapper for the primary motor circuit operated by a low-voltage magnet coil, and it has a number of switches controlling the resistance in the secondary motor circuit. The secondary circuit of the motor is usually designed for comparatively low voltage, and therefore the usual clapper type construction, as illustrated, may be employed.

The secondary switches are controlled by three-phase series relays connected and constructed as described above.

Where the supply circuit has a voltage above 550, it is necesary to employ a step-down transformer which supplies current for the pilot circuit operating the magnets. In a previous paragraph we have already touched upon the considerations which bear on the construction of such high-tension switches.

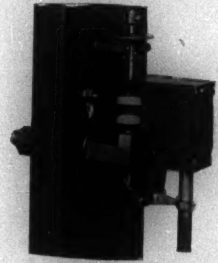
A type of controller which finds more frequent application in steel mill practise than the non-reverse automatic starter is the reversible automatic controller. Its usual application is for intermittent service requiring very frequent starting and, quite often, speed regulation at all controller points. The service performed is very much more severe than that of non-reversible controllers. Instead of putting in one switch for the primary circuit, two switches suitably interlocked are used, one for each direction of rotation of the motor. The secondary circuit of the motor is controlled in the same manner as on the non-reversible controller. The resistance has to be designed with a considerably heavier capacity, and in some cases requires even continuous carrying capacity on all points. Such controllers are used in connection with mill tables, cranes, hoists and other machines.

The various applications of this controller in steel mills and



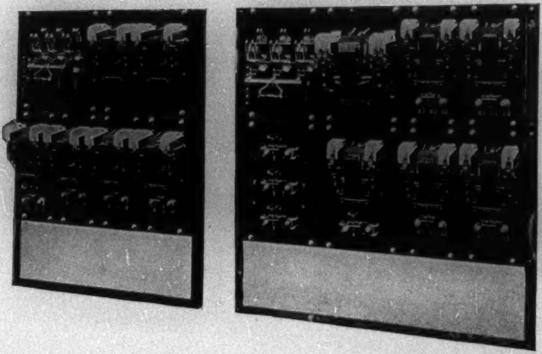
[SIMON]

FIG. 8—2200-VOLT TRIPLE-POLE AIR-BREAK REVERSE SWITCH



[SIMON]

FIG. 9—PRIMARY SERIES RELAY



[SIMON]

FIG. 11—CONTROL PANELS FOR ELECTRICALLY-OPERATED SHOVEL

allied industries require many special features, and we shall further discuss some of the typical applications of these controllers.

Electrically-operated shovels and drag lines have not been discussed very much in electrical literature, though they present some very interesting problems, and since the writer has some interesting data on hand, we shall discuss these. The first shovel installations used direct-current motors, and it was considered not only desirable but absolutely necessary to build the controller and the motor so that the electric shovel would exactly duplicate the operating cycle which was found the most suitable for the older steam machines. The first installations were not quite as successful as had been expected, and designers have gradually come to the conclusion that it is best to modify somewhat the operating cycle of the shovel, or, at least, the mechanical design of the shovel in order to fit the electric motor. On account of the necessity of transmitting the power to the shovels, usually over long distances, most of the shovels which were installed in late years are equipped with alternating-current motors, and these are the ones which we shall treat here.

Shovels of capacities ranging from 60 to 100 tons are equipped with three motors, one for hoisting, one for the swinging and one for the thrust motion. Except on the smaller machines, all motors are controlled by full automatic controllers. On the smaller machines, the thrust motion has a drum controller.

Fig. 11 shows the controller panels for a 100-ton shovel. The main hoist motor is equipped with a non-reversible, automatic self-starter, which in turn is controlled by a multiple speed master drum. This controller is provided with a number of "jamming" relays, which reinsert resistance in the rotor circuit of the motor when a certain maximum torque is reached, so that if the motor is stalled by encountering an excessively heavy obstruction in the stone bank, the torque is automatically increased up to the maximum torque which the machine can stand. This avoids the stalling of the motor with the resistance short-circuited, which would result in the opening of the circuit breaker and the loss of power. The hoist motor is non-reversible, because there is always a sufficient load on the motor to overhaul it and to lower the bucket of the machine when the brakes are lifted and the power supply to the motor is cut off.

The swinging motion is controlled by a full-reverse automatic self-starting controller, also provided with a master drum controller which permits of running at any speed. The use of current-limit relays has proved particularly advantageous in this instance, because the inertia of the boom of the shovel is quite high, and therefore it would be quite possible for the operator to accelerate too fast and to lift the shovel off the track, if no current-limit relays were provided for.

This is still more important in case of the drag line, the boom of which has a still greater inertia on account of its extreme length. In other respects the drag line operation is the same as that of the shovel, except that it has no thrust motion, the bucket being operated only by the manipulation of the hoisting machine.

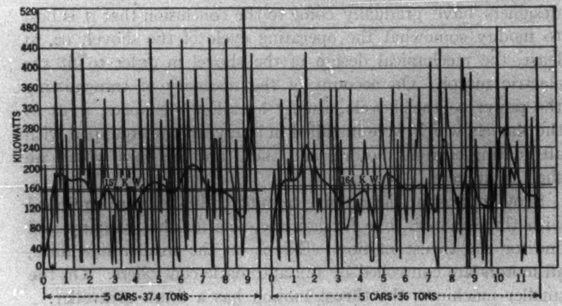


FIG. 12—CURRENT CONSUMPTION OF AUTOMATIC SHOVEL

The thrust motion of the shovel is also controlled by a reverse controller with a few steps. In this case it is designed so that the motor speed is about inversely proportional to the torque, and therefore the motor is run with sufficient permanent resistance in the secondary circuit so that its speed-torque curve with the controller in the maximum speed position is nearly a straight line, and the motor exerts the maximum torque when stalled. In this way it is possible always to have the bucket follow the uneven curvature of the bottom of the pit, when the hoisting machine is operated, without the danger of wrecking the machinery by exerting undue stresses on the thrust or hoist motion.

The diagram of Fig. 12 relates to the power consumption of an electric shovel equipped with automatic controllers. A second shovel of the same bucket and motor capacity and of the same weight, is of German make, and we therefore shall call it the "German" shovel, whereas the first shovel with automatic controllers is of American make, and we call it the "American" shovel. The tests were made on high-grade iron ore in the Swedish iron mines in Lapland, and the following results were obtained:

COMPARISON OF ELECTRIC SHOVELS IN SWEDEN

	German				American			
Maximum peak	390	kw.	380	kw.	520	kw.	480	kw.
Next four peaks	370	kw.	340	kw.	460	kw.	420	kw.
Amount of excavation	36.5	tons	36.5	tons	37.4	tons	36	tons
Average load	105.4	kw.	105.4	kw.	157	kw.	164	kw.
Time to load 5 cars	20	min.	22	min.	9½	min.	11¼	min.
Kw-hr	35.1		38.6		24.8		30.8	
Kw-hr. per ton	0.96		1.06		0.662		0.855	

It will be noticed from the above table, that, while the maximum current peaks of the automatic shovel are higher, the shovel handled nearly twice the amount of material in a given time that was handled by the non-automatic shovel, and the power consumption per cubic yard of material handled is considerably less on the automatic shovel. If the cost of power, depreciation, interest, labor and other items, were added, it would be found that the operation of the automatic shovel is considerably cheaper than the operation of the non-automatic shovel, and that in this instance, and in a good many others, the increased cost of the more expensive installation more than pays for itself within the first year.

An important machine for steel mills and mine service is the electrically driven pump. When installed in the mine the pump controller has to be designed along the same lines as the controller for mine fans, and special provision has to be made for automatic re-starting after failure and subsequent restoration of the current supply. In some instances it is possible to have the pump started by hand operation under no-load conditions. In this case, the operator will close the inlet and outlet valves of the pump before it is started. We have reference here primarily to centrifugal pumps, which are used more and more universally today. Under the conditions outlined above, the pump requires only a very low starting torque and therefore it is very often possible to employ a squirrel-cage motor with compensator type starter. Under some special conditions the pump may even be started with a very low torque without manipulation of the inlet and outlet valves, and it may, at the same time, be desirable to use an automatic controller, thereby doing away with the necessity of a constant attendant. In recent years automatic compensator type starters have been adopted and have proved to be quite successful. It has been found that such starters may be operated either with current- or time-limit relays. In controlling the acceleration, the current-limit relay has the advantage of keeping the current peaks always within predetermined limits irrespective of the time it takes the motor to accelerate, and irrespective of any possible variations in the starting torque. On the other hand, if for any reason the starting torque required should increase appreciably, the current relay might not permit the controller to apply full voltage to the motor terminals and, therefore, the motor would always run on the low-voltage tap of the starter, and both the motor and the starter might ultimately burn out. This danger is enhanced by the fact that the current of the motor changes only slightly during the first part of the accelerating period and therefore the current relay has to act on very small changes of current; in other words, has to be very sensitive. This extreme sensitiveness cannot always be maintained under ordinary operating conditions, and with only disinterested supervision it seems more desirable to use the time-limit relay acceleration for such controllers, despite some inherent disadvantages which such controllers undoubtedly have. If the starting torque required of the motor is liable to vary, the current which it takes with the time-limit relay also varies. This is the main objection to the time-limit relay acceleration; but, on the other hand, as long as the relay operates at all, it is not possible for the motor to run indefinitely on the starting tap of the starting transformers, but after a certain time, which normally should be sufficient to bring the motor up to proper speed, it will be brought to the full speed point, and the transformers are cut out, thereby eliminating the danger of burn-out due to low voltage.

On the other hand, if the motor should not start at the first controller tap, it would start when it is thrown on a higher tap or on the full voltage. This may not be always the best thing for the mechanical parts of the machinery, but with proper mechanical design, it would in no event be so disastrous as the stalling of the motor and subsequent burning out, due to the inability to start at low voltage, as in the case of current-limit acceleration.

While we are dealing with the handling of raw materials and the operations in the mines, we wish to call attention to a very interesting problem involving semi-automatic or automatic controllers for an entire series of motors; this is the motor drive of a line or several lines of belt conveyers. In cases where a great many belts are driven by individual motors, it is desirable to prevent an accumulation of material on any one of these belts, due to the shut-down of its corresponding motor. It is therefore necessary to interlock the controllers for the various belts in such a manner that in case of stoppage of any motor all preceding belts also come to a standstill, stopping the delivery of material to the belt in trouble, so that the motors can only be started in reverse rotation to that in which the material is handled by the various belts. A number of such installations have recently been completed for coal and ore belts. In one notable installation, covering some thirty belts, the interlocking spoken of has been accomplished by means of centrifugal governors, which are driven by the countershafts on the belts, and which when standing still, open any interlocking circuit which is in circuit with the preceding motor. In another instance, all belts, crushers, etc., belonging to the system are controlled by compensator type starters, the no-voltage releases of which are interlocked so as to get the results desired as outlined above. This shows to what extent automatic controllers can be adapted to the steel mill industry to supersede inefficient labor.

The electric drive of the coal and ore bridge has received a great deal of attention of late years. This problem is important because most of the raw material is transported by water on the Great Lakes, and since the shipping season is comparatively short, it is desirable to load and discharge vessels as quickly as possible to get the highest rate of return from them. The loading and unloading equipments therefore have been designed to enable much more rapid handling of material than is found anywhere else in the world. I hardly need to mention here the feats that are being accomplished almost daily in the unloading of ore and coal vessels, and there is being presented today another paper dealing particularly with coal and ore handling machinery.

One of the most important installations in the blast furnace plant is the skip hoist, on the operation of which depends the smooth running of the furnace. Skip hoists are also used in

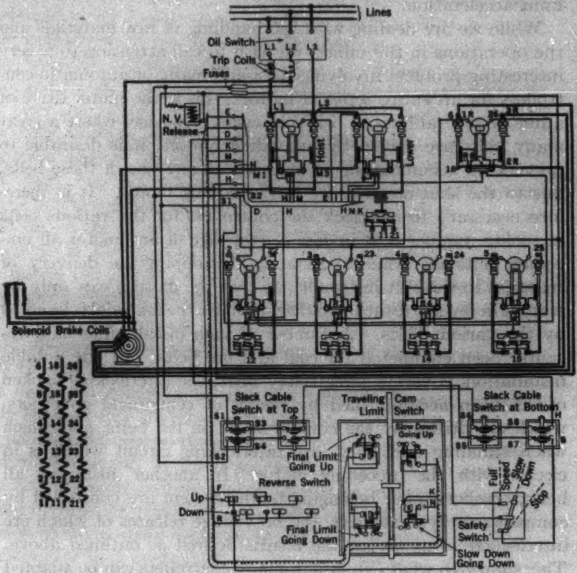

Lines
Oil Switch
L1
L2
L3
Trip Coils
Fuses
N. V. Release
Hoist
Lower
Solenoid Brake Coils
Slack Cable Switch at Top
Travelling Limit
Cam Switch
Slack Cable Switch at Bottom
Slow Down Going Up
Final Limit Going Up
Reverse Switch
Up
Down
Final Limit Going Down
Safety Switch
Full Speed
Slow Down
Stop
Slow Down Going Down
12
13
14
15

FIG. 13—CONNECTION DIAGRAM FOR ALTERNATING-CURRENT SKIP HOIST

mines, cement plants, and so on. The writer is not familiar with any alternating-current installation on blast furnace skip hoists, but there have been made some notable installations of skip hoists, particularly in cement plants.

Fig. 13 shows a diagram of a balanced automatic skip hoist in a cement plant. These hoists are designed for a maximum pull on each rope of approximately 11,000 kg. (25,000 lb.).

These rope pulls are balanced by the weight of the descending skip on the other side, so that at the time of starting, the unbalanced rope pull which the motor has to handle is approximately 7000 kg. (17,750 lb.). Each hoist is designed to handle 7200 kg. (16,000 lb.) of stone per trip. The skip weighs 5400 kg. and the incline is 67½ per cent from the horizontal. The hoists are equipped with a 125-h.p., 550-volt, 60-cycle, three-phase motor, continuous duty, and the gear is designed to give a maximum rope speed of 200 ft. per min. The actual hoisting distance is 139 ft., and each hoist is designed for a capacity of 400 tons per hour. The operation of the hoist is entirely automatic, the starting being initiated by the loaded car, and a solenoid brake is mounted on the motor shaft to bring the hoist to rest. The hoist stops always within three inches of the same point. By slightly overloading the skip each hoist has handled 4700 tons of stone in ten hours.

Another very important application is the electric drive of mine hoists. Where very large powers have be to handled special arrangements are usually made, such as the installation of an Ilgner system, which is always to be recommended, except where the power supply is practically unlimited, and can therefore take care of the rapidly fluctuating load of the hoist. For smaller powers the slip-ring type motor is quite suitable, with a series-relay type reversible hoist controller. The satisfactory operation of the series relays may best be judged by the fact that in a certain installation the current peak at starting never exceeds 80 amperes, the maximum current which is allowed by the power company. Some figures relating to this hoist may be of interest. The hoist was guaranteed to require not in excess of 90 amperes when handling 3200 kg. (7000 lb.) when operating balanced or unbalanced; the maximum rope pull at the drum would not exceed 3700 kg. (8200 lb.) in the latter case. The current input specified is measured on the primary side of the transformer, with a primary voltage of 2080 volts, at 60 cycles. The calculations showed that, on the guaranteed condition of load, the maximum current peak should not exceed 80 amperes, which checks up exactly with the graphic curve. The motor is 200 h.p., 440 volts, 60 cycles. The controller, in addition to the switches handling the motor circuits, is equipped with a high-tension type magnet switch which cuts off the current of the transformer whenever the motor stands still, so as to avoid the primary losses of the transformer.

The most important motor application in the steel mill is the main drive for the rolling mill. A great deal of discussion has taken place during the last ten years regarding the most advisable arrangement for this installation. European practise today uses the two-high mill driven by reversing direct-current motors, which are supplied from a motor-generator set with flywheels, and which are controlled according to the variable voltage system. On the other hand, in this country, operating men have preferred a three-high mill driven by a constant speed motor running always in the same direction. This enables the use of high-voltage alternating-current motors directly supplied from the power station and eliminates the motor-generator, thereby eliminating several links from the transmission system and increasing its insurance against breakdown. It is usually pointed out that such an installation is more reliable and cheaper in operation on account of its higher efficiency, but it is the writer's belief that there is no universal solution for all cases, and there can be no doubt that where conditions are suitable, the Ilgner system is equal if not superior to the American system of constant-speed motors with the three-high mill.

We do not propose to discuss at length any of these installations, but we give operating data of such an installation, consisting of two 500,- one 750- and one 1000-h.p. motors. The motors are 2200-volt, three-phase, 25-cycle machines. The controllers are arranged for forward and reverse rotation and also for automatic braking. The reverse is required only for emergency; for instance, when the mill becomes clogged. In this case, the primary circuit of the motor is reversed and it is possible to accelerate the motor up to full speed in the reverse direction, if this should be desired.

Automatic braking is obtained by energizing two of the three phases of the stator with direct current from a low-voltage source of supply, and then gradually cutting out the resistance in the rotor circuit of the motor. The motor then operates as a synchronous generator with variable frequency.

A number of steps of permanent resistance are employed, which may be cut in and out by knife switches. The purpose of this resistance is to adjust the average slip of the motor, so as to enable the flywheel, which is put on the motor shaft, to smooth out the current peaks during the cycles of operation. Depending upon the material to be rolled, the average load on the motor is higher or lower, and therefore it becomes necessary to adjust the slip resistance to the average load.

The controller is operated through a master drum having two handles, one for acceleration, and the other for setting the direction of rotation. This second handle will also complete the dynamic braking connection in its center position. The two handles are interlocked in such a manner that the accelerating drum must always be returned to the position in which all accelerating switches are opened and all resistance inserted in the rotor circuit before the direction switch can be operated. The acceleration and the dynamic braking may be entirely automatic. It is only necessary for the operator to bring the accelerating drum handle to the full speed position, and the motor is then accelerated or slowed down by the automatic action of the current-limit, relay in the secondary circuit. This tends to keep the torque, during acceleration and braking constant. The high-voltage switches employed in the primary circuit of this installation have been described before. It should also be pointed out that the controller is equipped with overload relays connected in such manner that the drum has to be returned to the off position to enable restarting after the overload relays have operated.

Some data relating to the motors are as follows: One 500-h.p. motor, 365 rev. per min., flywheel 10-ft. diameter, 10,000-lb. rim; one 500-h.p. motor, 12-ft. 8-in. diameter flywheel, 30,000-lb. rim; one 750-h.p. motor, 244 rev. per min., 12-ft. 8-in. flywheel, 30,000-lb. rim; one 1000-h.p. motor, 180 rev. per min., 17-ft. flywheel, 60,000-lb. rim.

The 1000-h.p. motor requires about five minutes for its acceleration with an initial inrush of 750 kw., and subsequent peaks of approximately 600 kw. The current peaks of the other motors are proportionate. According to the report of the engineer in charge, the controllers for these motors, after the installation was completed and adjusted, never required any attention, except usual inspection, during the five or six years of installation. This would indicate that alternating-current controllers can be built today sufficiently reliable for the most severe service conditions.

We have outlined in this paper some of the typical installations of alternating-current controllers, and we have touched upon some of the typical points in the design of such controllers, and the author will be glad if the paper furnishes the basis of a general discussion on the subject.

Presented at the 308th meeting of the American Institute of Electrical Engineers, Pittsburgh Pa., April 16, 1915.

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THE ALTERNATING-CURRENT COAL HOIST

BY RAYMOND E. BROWN

Abstract of Paper

The paper describes an alternating-current coal hoist recently installed near Pittsburgh in which dynamic braking is employed. The brakes and clutches are operated by compressed air, which permits of a maximum rate of operation and also makes feasible the use of various safety devices,

The electrical equipment of the coal hoist must be capable of continuous operation at the maximum speed and any attempt to insure against motor or brake trouble by providing excess capacity simply results in the motor being operated at that increased capacity. The control in lowering the empty bucket at high speed must be accurate enough so that it can be slowed down quickly without damaging the barges or steamers in landing. With a friction brake the only way to avoid striking too hard in landing is to make a complete stop before reaching the bottom, thereby causing an appreciable loss of time, which is entirely avoided by the use of dynamic braking. In the case of the plant described the control has proved sufficiently accurate and exact so that a complete cycle of the hoist trip due to the overlap of hoisting and racking movements can be made in 40 seconds instead of the estimated time of 50 seconds.

THE COAL hoist, and of course the ore-handling bridge or unloader, is different in several respects from most other machines for hoisting or transferring materials, and also from nearly all other applications of electric or steam power.

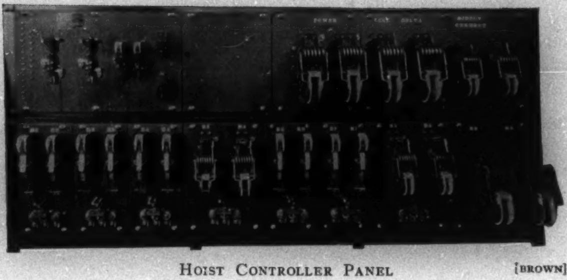
One of the points of difference is in the necessity for a very accurate analysis of the cycle of operation, in order to obtain a motor of the proper speed, torque and heating capacity. In the case of a motor handling any material in its progress through the mill, the amount of work it will have to do is, to some extent at least, determined or limited by the apparatus which brings the material to it or takes it away to the next operation. Consequently, by providing some excess over the rated capacity, the motor can be given what we may speak of as a factor of safety against overheating. In the case of the hoist, however, the material in front of it is, we may say, unlimited, as it is usually brought in in quantities sufficient to permit the hoist to operate at its maximum possible speed for a period long enough to cause any trouble that can arise from overheating of either the electrical or mechanical parts.

The electrical equipment consequently must be capable of continuous operation at the maximum speed which the weight lifted, the motor characteristics and the operators movements will permit. Any attempt by the designer of the hoist to insure against motor or brake trouble by providing an excess in capacity over and above that specified by the purchaser simply results in the machine being operated at that increased capacity as long as any material remains in front of it.

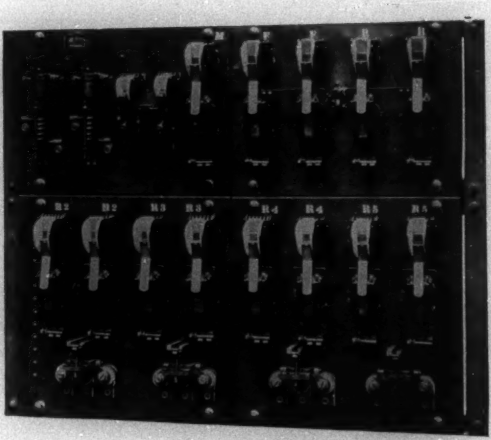
One other point wherein the coal or ore hoist differs from other hoists is in the lowering of heavy unbalanced loads at high speeds and yet under very exact control. The furnace or skip hoist when not counterbalanced approaches this condition, but on account of working between fixed points it can have limit switches to provide for the slow-down and stop. The coal or ore hoist on the other hand has no fixed elevation for the material which it is digging, consequently it is still necessary for the operator to control the lowering of the bucket. The ladle crane lowers its full load, but its speed is very low. The coal or ore hoist must lower an empty bucket weighing from one-half to two-thirds as much as the load hoisted, and must do this at a speed from 300 ft. (91.5 m.) per min., to 500 ft. (151.5 m.) per min. The operator's control over this speed must be accurate enough so that he can quickly slow the bucket down to land it on the frail wooden barges used on our rivers or on the comparatively thin steel plating of the lake steamers.

The statement has been made, and probably is still believed by some, that the friction brake, operated by foot or hand, is the most reliable control for lowering a bucket. With dynamic braking, each notch on the controller gives a uniform lowering speed, and since the load being lowered is always the same, it follows that the speed on any given point is always the same. On the other hand, no uniform pressure or position of a foot brake can fail either to retard the load or permit it to accelerate, because even if the operator does accidentally produce a torque exactly balancing that of the load, the coefficient of friction changes as soon as the brake temperature rises, and consequently the balance is destroyed as soon as it is established. A speed variation of 20 per cent produces a change of 44 per cent in the kinetic energy of the moving masses, and this must be absorbed by the brake. Since the operator can not estimate the speed within 20 per cent and has no means of producing any definite

PLATE L.
A. I. E. E.
VOL. XXXIV, 1915


POWER
LINE DELTA

HOIST CONTROLLER PANEL [BROWN]


M
R2
R2
R3
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R4
R4
R5
R5

RACK CONTROLLER PANEL [BROWN]

speed while lowering with a friction brake, it is evident that the only way to avoid striking too hard is to make a complete stop before reaching the bottom. This causes an appreciable loss of time which is entirely avoided when dynamic braking is used. It is unnecessary to dwell at any length on the effect on the machinery and ropes of the shocks caused by sudden applications of the brakes, or on the expense of replacing the brake lining and occasionally the brake wheels.

Reference was made earlier in this paper to the question of heat-absorbing or rather heat-radiating capacity of motors and brakes. Another of the advantages of dynamic braking is that the heat-capacity of motors seems to be capable of more accurate determination, or at any rate, is more accurately determined than is the case with the ordinary friction brake, as it has not been a very rare occurrence for a friction brake to require some changes before it would lower the bucket on a high-speed hoist without overheating.

The purpose of this paper is to describe (to some extent from an operative view-point) a coal hoist recently installed for the Union Railroad near Pittsburgh. This is a duplex tower containing two independent hoists taking coal from river barges and loading it into railroad cars. The coal can be crushed and screened into various sizes or may be loaded direct without any preparation. The entire plant is operated by 220-volt, 25-cycle, three-phase a-c. motors.

The two engines for handling the buckets are located in a room about 28 ft. (8.5 m.) by 42 ft. (12.8 m.) at the top of the tower. Below this are the trolley tracks, which extend out over the river as a fixed boom or cantilever. Below these tracks in the tower is the coal hopper, which is provided with two discharge spouts. The mechanism below this point, like that above the hopper, is in duplicate, so that a description of one side will suffice.

When the coal is to be crushed it is conveyed to the top of the crusher by a pan feeder conveyor driven by a 7½ h.p. motor. The crusher is driven by a belt from a 150-h.p. 480-rev. per min. motor which has an auto-starter with separate transformer, and is protected by a three-pole a-c. contactor-type circuit breaker with push-buttons for resetting overload and for closing the circuit breaker.

The crusher delivers to a set of shaking screens, operated by eccentrics on a shaft driven by a 25-h.p. motor. When it is not necessary to crush the coal, it is fed by another type of feeder directly from the hopper to the shaking screens.

The auto-starters and circuit breakers for the motors driving the feeders and shaking screens on both halves of the plant are grouped together at a point where the attendant can see the coal passing into the cars, and he can, by pressing a button, stop the flow of coal to either of the cars. As the shaking screens in the two sides of the tower deliver to different tracks, the simultaneous loading of orders for different grades of coal is possible.

The bucket has an average capacity of 4 short tons (3650 kg.) and weighs about 11,000 lb. (5000 kg.). The closing rope passes around sheaves in the top of the bucket and in the vertically moving crosshead which is connected to the spades to give the necessary power for closing them. The ends of this rope pass over sheaves in the trolley, then to sheaves at the ends of the trolley track and to the closing drum in the engine room. The hold rope, which carries the open bucket, passes under a sheave in the top of the bucket and follows the same route as the closing rope, both ends being anchored on the hold drum. The hoist motor is connected to these two drums through two pairs of gears having a total ratio of 10 to 1, which gives the bucket a speed of 7½ feet (2.3 m.) per second. Each drum has an air-operated clutch, and there are two air-operated band brakes, one being on the hold drum and the other on the intermediate shaft or countershaft next to the motor. The operator has a valve for each clutch, and one for the two brakes. The construction of this valve is such that a partial movement of the handle applies the hold brake, and a complete movement applies both.

The rope arrangement is such that the trolley or racking movement is independent of the bucket engine. The rack engine consists of a 75-h.p. mill-type motor geared to a drum from which ropes lead to the two ends of the track and thence to the trolley. The drum is provided with an air-operated brake. The motor is controlled by a plain reversing contactor-type controller, with master controller in the operator's cab. This master controller, as well as that for the hoist, has a straight-line bevel-gear drive handle, so that the movements of the handles of the two controllers and the four air valves are all of the same character.

It may be of interest to follow out a cycle of operations, starting at the time when the bucket is ready to begin lowering. The hold brake valve is moved to the release position, and the hoist controller handle is placed on the point which has been found to give the desired speed. The bucket descends at a uniform speed, and if the coal is deep enough to prevent injury to the boat, the speed is not checked until just before the bucket strikes the coal, when the controller handle is moved to the maximum braking position and the brakes are also applied. When working near the bottom of the boat, the increased dynamic braking is applied earlier, so as to land the bucket without shock. The hold clutch is now released with the left hand while the right moves the controller handle to the proper point for closing. When the bucket is closed the left hand returns the clutch valve handle to its application position, while the right applies full power for hoisting. The left hand is now free to rack the trolley in toward the hopper at the proper time. When the bucket is high enough, the hoist controller is returned to its off position, and as the bucket slows down the hold brake is applied. The bucket by itself would stop its upward motion in about a foot (0.3 m.), but the momentum of armature, gears and drums is sufficient to hoist it several times this amount after the power is shut off.

The bucket is dumped by releasing the hoist clutch, which is applied as soon as the bucket is open. During this time, the left hand is stopping the trolley and racking it out again. If followed out closely this cycle will be found to require only six changes in the position of the operator's hands—that is, six shifts from one handle to another.

All of the handles move in vertical planes toward and away from the operator, and none of them require any appreciable effort.

This system of bucket engine construction permits the use of one motor when the necessary amount of power is available in one unit, and permits the use of two or even more motors if necessary, without any change in the scheme of operation. It allows the full power of hoist motors to be used for the final closing of the bucket where the material being handled is such that this amount of power can be utilized. It also permits the full torque of hoist motors to be used for retarding the speed of the bucket while lowering. In cases where the necessary amount of power can be obtained in one motor, the cost of motor and controller will be considerably less than where the type of engine requires two motors and two controllers. Also, when the hoist is so large that two motors are necessary, the cost of the controller equipment is less if the two motors are handled by one controller than where two separate controllers are needed. Where the two drums are independent, each having its own motor and controller, lowering requires the manipulation of two handles instead of one, as one motor must pay out the slack closing line while the other acts as a brake.

The use of air for operating brakes and clutches permits the operator to maintain the maximum rate of operation throughout the day, to a much greater extent than can be done where the severe labor of manipulating clutches and brakes by hand or foot is required of him, especially when handling heavy loads. It also makes it feasible to install various safety devices. In this plant the hold brake is automatically applied if the bucket is hoisted too high, also when the overload relay cuts off the power to the motor, and in case of loss of voltage on either the a-c. lines or the d-c. control circuit. Limit switches on the trolley track cut off power to the rack motor and apply the air brake on the drum.

A small motor-generator set is located in each half of the engine room, supplying 220 volts direct current from a six-kw. shunt-wound generator for the coils of the contactors on the hoist and rack controllers. It also excites the fields of the other generator, a nine-kw. 15-volt compound-wound machine, which supplies the low-potential direct current to the stator windings of the hoist motor during dynamic braking. These two generators are direct-connected to a 20-h.p. 710-rev. per min. a-c. motor.

Air is supplied by a two-cylinder compressor driven by an a-c. motor. The compressor governor is arranged to lift the inlet valves in the cylinder heads instead of stopping the motor as is customary in d-c. operation.

The hoist engine is driven by a wound-rotor induction motor with an intermittent rating of 315 h.p. The calculated cycle of operation includes six seconds closing at 150 h.p., three seconds accelerating hoist at 425 h.p., eleven seconds hoisting at 340 h.p., and twelve seconds lowering, at 130 h.p. braking. These values are for power at the motor pinion.

The hoist controller consists of the master switch in the operator's cab, and a panel in the engine room, with the necessary resistance located immediately behind the panel. The panel carries the necessary contactors, interlocks and relays. There are three single-pole contactors to connect the stator windings to the a-c. lines; one contactor to open the stator windings at one point and two contactors to connect the d-c. lines from the 15-volt generator to the stator when this delta switch is open. Each step of resistance with its pair of contactors makes a star connection between the three busbars connected to the slip rings on the rotor. Resistance is reduced by adding more steps in parallel with the first, and the last step is a short-circuiting contactor. There are five steps in accelerating the hoist, and four points of dynamic brake control. Each of the accelerating switches except the last is provided with an individual accelerating relay. The panel also has no-voltage relays in the a-c. and the 220-volt d-c. circuits, and two overload relays.

On the lowest floor of the tower is located a barge shifter engine, consisting of two drums with clutches and brakes geared to a 30-h.p. motor. This is controlled by a face-plate reversible controller, and the brakes and clutches are hand-operated. Ropes pass along the face of the dock and around sheaves and are attached to the barge which is being unloaded.

The beginning of actual operation of this plant was looked forward to by its builders with considerable interest and possibly some anxiety. The speed was to be 50 per cent higher than had been previously used in any a-c. hoist with dynamic braking, and there had been rumors that the controller designers had encountered some very difficult problems in working out the control. When the first a-c. hoists with dynamic braking were built in 1909, they required a considerable period of adjusting and a number of changes. On account of the higher speed of this hoist, and as this control was being developed by another company, the builders of the hoist were naturally anxious as to the results that might be obtained.

The control equipment had been checked over by a representative of the controller company, and on the day that coal was to be hoisted he and the writer were present to see what would happen. One accelerating relay on the hoist panel required a slight adjustment to smooth out a peak which occurred when the last contactor closed, and a similar adjustment was made on the rack controller. It was not found necessary to make any change in the amount of resistance in any of the various steps and except for the adjustments mentioned, which required only a few minutes' time, the controller is operating exactly as sent from the factory.

As to the accuracy of control over lowering, it may be sufficient to say that the maximum speed is higher than the hoisting speed, and the minimum is low enough to land the bucket on the thin planking of the river barges without perceptible shock. In spite of the wide range in lowering speed, and the small number of steps on the dynamic braking control, the handle may safely be thrown to the maximum braking position while the bucket is descending at its maximum speed. The use of separate contactors for braking permits their accelerating relays to be adjusted so that torque on the motor will not be brought above the pull-out point.

As a result of the exact and accurate control which the operator has over the bucket movements, this hoist has shown itself to be capable of continued operation on a somewhat shorter cycle than was estimated. This is due to a large overlap of hoisting and racking movements, and a slightly higher lowering speed. While the cycle necessary to make the required capacity was 50 seconds, the hoists can make trips in 40 seconds.

A few words in regard to the first application of dynamic braking to a-c. hoists on a large scale may be of interest. A number of five-ton coal bridges were built by the same company about six years ago for several coal docks in Superior, Wis. The buckets were larger than any previously used for unloading coal from lake boats, and the speeds were higher. The use of friction brakes for lowering the buckets was found to be the cause of considerable expense, not only for replacing the brake lining, but also for replacing the brake wheels, drums and shafts which were occasionally broken as a result of trying to make too quick a stop after attaining an unusually high speed. The castings were made heavier, and the new shafts were of nickel-steel, but even these could not make the operation satisfactory.

Regenerative braking was tried, but the speed resulting from this was high, and very careful manipulation of the controller was necessary. Lowering with the motor on the first point in the hoisting direction was naturally found to be extravagant in the use of current and hard on the motors.

It was finally decided to place small motor-generator sets on the bridges, to apply low-voltage direct current to the stator windings and to change the controllers so as to provide for this system of braking. After this new apparatus was installed and adjusted, the results were such an improvement in the control over bucket and trolley that brake trouble became a thing of the past and the output of these bridges reached a point considerably higher than had been expected.

Reports have recently been received from one of the companies operating these bridges that, after making careful comparison between the records of their a-c. plants and the later ones built on d-c. docks, in figuring on new installations they would consider an a-c. plant to be equally as desirable as one operating on direct current.

DISCUSSION ON "ALTERNATING-CURRENT CONTROLLERS FOR STEEL MILLS" (SIMON) AND "THE ALTERNATING-CURRENT COAL HOIST" (BROWN), PITTSBURGH, PA., APRIL 16, 1915.

Raymond E. Brown: One of the papers presented made mention of the desirability of having motors of a sufficient size to operate part of the time at reduced load, to keep the commutator in good shape. The desirability of low temperature limits for rheostats was also discussed.

When the mill is buying electrical apparatus, it should be a comparatively simple matter to have recommendations like these carried out, but it is different with a manufacturer of cranes and hoists. He is making machines that contain various amounts or electrical apparatus, is obliged to sell against strong competition, and frequently finds, after including in his proposal a number of refinements that help to make economical operation and low cost of upkeep, that the various bids are merely reduced by the purchaser to a pound price basis and compared from that view-point alone.

You cannot expect a manufacturer to include in his product, whatever it may be, many refinements whose value is not yet well recognized by purchasers, unless they effect a saving in the balance of the machine or serve to increase its output.

In the discussion on screw-downs and roll-table drives, it was brought out that in some cases a considerable saving in power could be effected by using two small motors in place of one large one. This hoist, where the load will coast upward about eight feet after power is shut off, may at first glance appear to be another place where the same thing would be true, but it is not.

If the operator shuts off power at the proper time, the kinetic energy of the rotating parts, as well as that of the ascending load, may be completely utilized in hoisting the load, and the brake should be applied only in time to prevent the load from starting downward.

The heavy flywheel effect of the large rotor is also utilized in starting to hoist the bucket. The motor during the final closing of the bucket reaches a speed high enough so that, as it is slowed down by starting the bucket upward, it delivers some of its surplus energy and reduces the peak load occurring at the beginning of the hoist, which is ordinarily the maximum.

Where power is purchased, the rate is often determined by the peak load, and consequently there appears to be an economic advantage in the use of a single large motor for the hoist where there is sufficient head room to give the necessary leeway for coasting to a stop, even though many other parts of the mill are better off with motors having as small a flywheel effect as possible.

M. A. Whiting: Mr. Simon compared the solenoid-operated oil switches and air-break switches (or air-break contactors as they are sometimes known). His comparison is entirely favorable to the solenoid-operated oil switch. Now, in cases where an oil switch is satisfactory, a hand-operated oil switch has many advantages over either a solenoid-operated oil switch or an air-break contactor. In cases where solenoid operation is required in any case, the question is one between the design and cost of solenoid-operated oil switches and air-break contactors. There are certain cases where the air-break contactors are far more reliable and are preferred by the trade. Those cases are mine hoists and similar classes of work in which the number of operations per day is very large. In this case the carbonization of the oil is entirely eliminated by the air-break contactors, and the contacts are open to inspection at any time, so that wear can be more easily kept track of. Furthermore the wear on the tips of air-break contactors is in many cases less than the wear on the tips of corresponding oil-immersed devices to do the same work. This last statement is at variance with commonly accepted ideas, but tests have been made which tend to show that there is considerable difference in wear of contacts in favor of the air-operated contactors, surprising as that may seem. I am not prepared to state that that would be universally true, but at least there is some tendency in that direction.

The air-operated contactors as we use them are not to provide the ultimate rupturing capacity for a short circuit on the power system, but rather as control devices for making frequent starts and reversals. The ideal arrangement for such frequent operating control equipments is air-break contactors for forward and a reverse, with a normal design of oil switch for ultimate protection in case of the comparatively infrequent excessive overloads or short circuits.

As to the extent to which air-break contactors have been used, I can say that we have sent out over one hundred equipments, meaning over 200 contactors of the air-break type. One such pair of contactors is in use in a rolling mill equipment on the South Side in Pittsburgh, and a number are in use in this immediate vicinity, at Greensburg, Montour, and elsewhere.

A direct comparison of the air-break contactors and solenoid-operated oil switches for frequent reversing service is afforded by the experience on the Rand in South Africa. Complete American equipments of hoisting motors and control have been shipped within the last half-dozen years. In addition to this, since the time when such equipments have been shipped to South Africa and put in operation, a large number of orders have been received for nothing more than a pair of 2200-volt air-break contactors to be used to replace solenoid-operated switches of various foreign makes, principally German, I believe, to be used with existing secondary controls and existing hoist motors. Some minor modifications have developed for use at 3300 volts, and a number of such equipments are in use in America.

The use of such air-break contactors is more general in mine hoisting work than in rolling mill work, because, of course, the large 2200-volt induction motors in rolling mill work under ordinary conditions are not started and stopped with anything like the frequency of the average mine hoist motor. Nevertheless, there have been a few instances, even in rolling mill work, where these air-break contactors have been applied advantageously.

J. H. Albrecht: I would like to take exception to the statement Mr. Simon made concerning the accelerating relay as used in the secondary or induction motors. The relay he shows in his panel in Fig. 7 is the ordinary drop-out U type magnet, and we found it to be almost absolutely independent of frequency; that is, we can get definite and reliable current settings on the relay, independent of the frequency. We can go down as low as his cycle and a half, even, without having the operation of the relay affected and it does not chatter.

When you get down to the business of relay acceleration, I believe the single-phase relay is the simplest proposition, if you can get the relay to work satisfactorily. That type of relay on the secondary necessitates a lap of auxiliary contactors or butterflies on your secondary contact to provide the necessary safety and interlock, and that means a complexity of control wiring. If you go to the individual three-phase relay in the secondary circuit it means a complication of the strap wiring and the individual single-phase relay is the simplest, as far as connection, and I believe as far as operation is concerned.

Mr. Whiting is very correct in his statement of the superiority of the air-break switch over the oil switch, and I would like to emphasize the point he made about the necessity of putting an oil breaker back of your panel of sufficient ultimate breaking capacity to take care of any short circuit or any very great overloads. We have recently finished some very successful tests on air-break switches. We found that our switch which will carry 312 amperes will break 600 amperes, and we have succeeded in breaking 600 amperes at 5000 volts, 30 per cent power factor. You will realize that is a heavy inductive load, and the switch has successfully handled that with a slight wear on the contacts.

I believe Mr. Simon stated he got 50,000 operations on some oil breakers without any excessive deposit of carbon. I would like to know whether the figure is not exceptionally high for apparatus of that class. Taking the case of mine hoists, where the device is operated quite frequently, we get very great smoking of the oil at perhaps three or four day's operation, and smoking of the oil of course means carbonization and in some cases trouble in a short time. I would like the operating men who have had experience with these switches to give me an idea what is the average run of the oil in these switches.

R. H. McLain: "Jamming" relays are mentioned, and since

Mr. Simon does not discuss jamming relays very fully I think it would be well to add one point concerning them. I have heard of operators who consider that the jamming relay prevents strains on the apparatus which was being driven. I think it would be well to point out that these strains are prevented only in a certain measure. The jamming relay operates only after the strain has taken place and not before, so it really does not prevent the strain, it only prevents the continuation of the strain. Furthermore, after the jamming relay operates there is a flywheel effect in the armature that will carry the hoisting ropes, etc., for a slight distance further, and nothing will prevent this except the give in the apparatus, such as stretching of the ropes or slipping of something somewhere. I think it is well to advise the use of some kind of a slipping friction clutch between the motors and the driven parts where absolute protection is needed. There are certainly valuable features in connection with the jamming relays, because they will prevent a continuation of the strain, and still enable the bucket to hold on to its load. If a friction clutch is used, after the friction clutch slips a small amount, the jamming relay will prevent it slipping further, and thereby relieve the friction clutch of any wear. Consequently the friction clutch will remain in better adjustment and be better prepared to take care of the operation the next time.

In regard to current-limiting relays of the individual type for each accelerating contactor, I notice that the claim is made that with these relays an individual adjustment can be made to suit the conditions desired for accelerating as the various contactors are closed. The relay shown in the paper would operate as follows: After the first contactor closes, and we are depending on the current-limit relay to prevent the succeeding contactor from closing, this relay must pick up and open and control the circuit before the second contactor closes. In other words, it must beat the second contactor out, it must work faster.

The current relays shown seemed to be set at successively lower values, that is, the first relay might drop out at 105 amperes, the next 103, the next 102, and so on each seemed to set at lower values. Is it necessary with this kind of relay, in order to accomplish the result, that when the first overload is thrown on it will raise all of the relays and thereby eliminate the chance of having a contactor beat out a relay in the succeeding operations? If that is true, it seems to me that the claim that individual adjustments can be made to suit the conditions of operation is wrong, and that the adjustments really have to be made to suit the conditions of the relays; that is, adjusting each one at a successively lower value.

Another point Mr. Simon mentioned, and brought out more fully in the paper, is the use of d-c. operated contactors on a-c. motors. It seems to me that this introduces another link in the chain of things that might happen to prevent the operation of the coal hoist. He has a low-voltage generator to excite the a-c. hoist motor and a high-voltage generator to excite the field of this low-voltage generator, and also to supply d.c. for operating the contactors. If anything should happen to this high-voltage d-c. generator, it would put everything out of commission. There would be no power with which to operate the contactors, and certainly no power with which to operate the dynamic brake. Now, if alternating current were used for the contactors they could continue to operate the hoist by means of mechanical brakes for lowering for a short time, or at reduced output. In that way, there is an additional link in the chain.

Another advantage of a-c. operating contactors is that no complications at all are required to give no-voltage protection. For instance, if the a-c. power fails and the d-c. power does not fail, and then the a-c. power returns, it is necessary that all the contactors should have dropped out and come back in sequence. In order to do this with a-c. contactors no extra complications are necessary, but with direct current, some extra relays are required.

Another point is the question of using accelerating rheostats connected in parallel rather than in series for hoist work. The parallel method has the advantage of making it possible to use divided circuits and small currents, and therefore the contactors can be small and of low cost, but it has this disadvantage, that one leg of the rheostat, if called on in an emergency to carry the motor at reduced speed for a considerable time, does not have the benefit of the capacity in the other legs to help it out; whereas if you had the rheostats in series and cut the successive blocks by the contactors, all the capacity of the rheostat, all the weight of the iron would be in service when running at reduced speed, and this is certainly an advantage in regard to rheostats.

Another disadvantage is that it takes a pretty good mathematician to adjust rheostats connected in parallel if anything goes wrong, whereas when they are connected in series it is only a case of sliding a tap and experimenting with each tap as you slide it.

I certainly think that Mr. Brown's coal bridge has marked quite an advance in a-c. coal hoists as to the speed attained, and that it is quite remarkable to see how coal bridge builders can calculate capacity that they are going to unload, with all the variable factors that they encounter. The manufacturer of electrical coal hoists has a hard job to predict all of the variable factors which he encounters, the varying shapes of the boat, and the uncertain quantity of the human element, and he is doing pretty well if he will guarantee some capacity near to what is actually required. The temptation of these men who want to design reliable apparatus is to guarantee away above the capacity, so they will be sure to take account of all these factors, and it indicates a great deal of skill when they don't have to guarantee away above the requirements in order to make sure of meeting all of them.

W. C. Kennedy: The discussion of Mr. Simon's paper by the last two speakers brings up a point which is of great interest to the manufacturer. I refer in particular to the statement made that air-break high-tension switches are not circuit breaker devices, but that they should be installed in connection with hand operated circuit breakers to take care of emergency conditions.

That question is not one which pertains to a difference between high-tension oil switches and high-tension air-break switches, but rather is a difference between a magnetically operated switching device and a hand-operated or circuit closing switch. It is impossible to make a magnetically operated switch, either direct or alternating current, that will be a good circuit breaker to take care of emergency conditions and at the same time be a magnetic switch of good design. This is true because, in a switch movement operated by a magnet or other electrical means, there is a certain amount of inertia in the moving parts and also it is not possible to operate this switch with as large an air gap as one that is closed by hand. For this reason a hand-operated circuit breaker should always be installed with either d-c. or a-c. equipments to take care of emergency short-circuiting conditions.

Another fact brought out in the paper was the operation of the individual series relay system. Probably there may have been a misunderstanding in regard to the arrangement of the control circuits which is not entirely clear at first inspection. During the ordinary operation of the equipment it is not necessary that the three-phase series-wound relays first open the control circuit to their respective switches and then close it again when the current in the rotor circuit has dropped to a value dependent upon the setting of the relay. Such an arrangement would be absolutely impractical. What actually happens is that the contacts on the magnetic switches have a certain lead and the series relay actually lifts a very short distance before the control circuit which it controls is energized. The only function, therefore, that the relay is to perform is that of dropping at the proper time, dependent upon its setting and in dropping it closes the circuit to the next succeeding accelerating switch.

The accelerating current curve of the 1000-h.p. motor shows distinctly that the dropping points of the various individual relays are different for the different switches. This is an advantage which this system shares in common with the present d-c. methods of acceleration, in that it is possible to vary the accelerating current during the period of acceleration and thereby adapt it to different load conditions. In fact with this system of three-phase accelerating relays, it is possible to obtain exactly the same accelerating characteristics as is at present obtained with direct current by the use of series, magnetic lockout switches or shunt-wound switches controlled by series relays.

In regard to the parallel connection of resistance, it is purely a case of resistance design. Sometimes it is very advantageous to use parallel connections, at other times it is just as advantageous to use series connections. For example, on motors of very large capacities, it is absolutely necessary to parallel groups of resistance. The main point to be gained by the parallel connection of resistance steps is that, as more accelerating steps are cut into circuit, the amount of available resistance material from which heat can be radiated is increased, whereas just the opposite is true where the resistance is connected in series.

On the other hand, for purposes of speed control, such as, for example, on a large motor where a slip regulating resistance is used, it is more advantageous to connect the resistance steps in series. Individual groups may be connected in parallel, but the resistance itself is in principle a series connection. If it is desired to run with 10 per cent slip on a motor with full load current, then the slip regulating resistance must dissipate approximately 10 per cent of the full load capacity of the motor; whereas, if 5 per cent slip is desired, then the resistance must dissipate only 5 per cent of the energy. It will readily be seen that in the second case only one-half as much resistance material is required as in the first case, therefore a series connection of resistance is more advantageous.

With a-c. work there is another point to be gained with a series connection of resistance. The series arrangement is very much easier to adjust than parallel connection, especially where resistance in three phases of the rotor must be considered. This is so apparent in some classes of work, especially hoisting service, that the hoist manufacturers almost invariably specify that the accelerating switches must be made of the proper capacity for a series connection of resistance. This necessarily increases the cost of the equipment, but adds to the simplicity of adjustment.

C. D. Knight: I desire to add a few words with reference to the oil- and air-break contactor situation. There is no doubt each of them has a very decided field, but where frequent operation is required the air-break type is the only one which can be successfully used.

I know of one installation consisting of a 2300-volt, 1000-h.p. motor, which had two reversing contactors in oil, the duty cycle being so heavy that the oil was continually becoming carbonized, which necessitated its replacement so frequently as to require one barrel of oil a week. These contactors were replaced with those of the air-break type, and apart from the occasional replacement of contactor tips, the maintenance charges have been practically nil.

I also have a record of a test made on a contactor immersed in oil, which was operated at 5000 volts, opening 50 amperes. At the end of three thousand operations, the oil, which was in a perfect state at the beginning of the test, presented a very thick, muddy appearance, and was unfit for further use. Where the duty cycle amounts in a mine to twelve or fifteen hundred operations a day, it can readily be seen that the above test represents about a two-day run for the contactors.

I wish also to make a few remarks with reference to the question of standardization. Mr. Pauly gave some figures, representing the various combinations which could be obtained with motors. In the case of the alternating current, his estimate ran up to from 7500 to 8000, due to the different voltages, frequencies and phases. In the case of magnetic control contactors those containing the same magnetic circuits, blow-out coils and contacts can be used for applications of a given current value. A different operating coil, however, must be designed for each voltage and frequency, which naturally runs into a great number of combinations.

We are all very optimistic regarding the future use of alternating current in steel mills, and I believe if we could standardize on three-phase, 25 cycles—I will say nothing at present about the voltage—we could simplify matters considerably.

W. F. Detwiler: I would like to hear from the manufacturers whether they have developed an automatic relay for protecting a two-phase or three-phase motor from operating on single-phase. Is there anything in that line that we can depend upon?

J. H. Albrecht: We have had several requests for a device of that kind, and while there are certain schemes,—one notably, a German scheme, involving four or five different relays,—we have yet to find a satisfactory solution for that proposition. I do not believe there is a satisfactory solution right now to prevent a motor from running single-phase; at least, I have never seen it, and I do not believe there is any in operation.

In regard to Mr. Kennedy's statement about using switches for circuit breakers, we do not advise using them for circuit breakers, of course. I have made interesting tests recently on d-c. contactors, and I have oscillograms showing a d-c. contactor opening a short circuit on a 500-volt power line, showing a peak of 60,000 amperes, at which point the oscillogram went off the scale. Out of respect to our power superintendent we cut the current in the next operation to 45,000 amperes, and then we reached the process at 30,000 amperes, and the contact was still partially there. That is an exceptional case, but shows what a d-c. contactor will do when it has to do it. On alternating current it would be a different proposition.

C. D. Knight: I wish to state that there will soon be a relay on the market to prevent motors running single-phase.

W. O. Oschmann: There is a certain field in which the solenoid-operated switch is preferable to the air-break contactor. Take cases where you have only twenty or thirty operations in a day's time and still expect some time to have reversing service on the motor, by the use of the air-break contactor you find it necessary to complicate your control circuit to the extent of providing some method of preventing the reversing contactor from coming in before the arc is interrupted on the contactor going out. We had a case where the arc held to such an extent that the incoming contactor closed before the arc was interrupted on the outgoing contactor, thereby producing a short circuit which not only burned the contactor, but also stopped all the synchronous apparatus on the system. The ordinary electrical interlock does not prevent the above trouble.

We eliminated the short circuit troubles by placing a small transformer across the motor circuit; the secondary of this transformer operates a small contactor which controls the circuit of the incoming contactor. It is evident that solenoid-operated oil switches would have avoided this complication.

I notice in Mr. Simon's paper that he uses a triple-pole contactor of the air-break type. We have found that these triple-pole contactors invariably break the arc on two poles only. Practically at no time will there be an arc on the three poles, therefore it seems a needless complication to use the additional pole, unless it is to take care of the voltage on the motor when the contactor is out, and this should be taken care of by an oil switch.

Regarding the question of primary relays versus secondary relays, I agree with Mr. Albrecht that a single-phase secondary relay is in a great many cases better than the three-phase relay. I note the statement made by Mr. Simon relating to the use of current transformers for large secondary relays. It does not seem as if this would be as good as the use of a single-phase relay in the secondary, at least two series transformers would be required and with the very low frequencies very large, bulky series transformers would be needed.

Graham Bright: I would like to make a few remarks regarding the interlock on air-break switches. I have had some experience in operating a hoist in which reversal was very quick, and, as has been mentioned, the arc sometimes holds long enough, where we have mechanical interlocking, to allow the other reverse switch to come in before the current is actually broken. That has occurred in a hoist where plugging was used to stop the hoist, and about once in every two thousand operations this short-circuiting took place. Of course, the voltage on the line dropped, which immediately robbed the motor of its torque, and only by the agility of the operator jumping on his foot brake was the cage prevented from causing a serious wreck. That was naturally trying on the nerves of the operator. I believe one method of prevention is to put an electrical interlock on reverse switches, which does not permit of the reverse switch starting in until the current is broken.

By electrical interlock I mean the true electrical interlock which depends solely on the current dying down to zero before the reverse switch can come in and not the so-called electrical interlock which depends upon the movement of fingers over plates making or breaking contact.

Mr. Brown made a statement I would like to take issue with, in regard to the weights and the inertia of the armature. He seemed to think it did not make much difference whether the armature was large with a great deal of inertia or small with little inertia. Heavy armature with high inertia will mean a slow rate of acceleration and retardation with a corresponding decrease in schedule speed. Light armatures with small radii of gyration will permit of quick acceleration and quick retardation, which in turn increases the schedule speed when the maximum speed is fixed. There is no question but that the rotating parts of the motor should have as low inertia as possible to keep down peak loads, and to keep the schedule as high as possible.

He mentioned a geared limiting switch used for stopping a hoist in case the operator went to sleep. Sometimes in hoists we have plenty of room above the dumping position so that in case the power is not thrown off at the proper time, the geared limiting switch, if placed in the circuit, will take care of the stop nicely. On the other hand, there are a number of installations which have been equipped without this point in view, in which the head sheaves are only a short distance above the dumping position. If we arrive at the dumping position at full speed there is not room to stop. If you apply the brakes you are too close to the head sheaves to stop and a geared limit switch under those circumstances is useless. You must produce some kind of a slow-down, and that has been accomplished in some coal hoists by a fly ball governor arrangement which works out very nicely. A geared limit switch is therefore in many cases of no value unless a positive slow-down is also provided.

C. D. Knight: I want to say, as far as I know, that electrical interlocks usually are used between these high-voltage air-break contactors—that is, in those I am acquainted with.

J. H. Albrecht: The point Mr. Bright referred to was the opening of the electrical interlock with the relay. We have an electrical interlock all right, to be held up by a series coil, and the series coil is in series with the line contactor relay and will drop out on occasion, but until the arc is extinguished and the current has died to zero in the working of the motor, this relay will hold up and not permit the other switch to be energized.

Clark S. Lankton: There has been considerable discussion concerning accelerating relays in the secondary control. My experience has all been with the single-pole relay. There is one thing I have noticed. At the start, when the motor is at low speed, the frequency will be high enough to get very good working conditions in the relay. When the motor approaches full speed, the acceleration is much greater, so that the last switches close very rapidly as compared with the switches on the low speed. It occurred to me that the reason we have good operation with a single-pole relay is because it is not of much use when the motor is nearly up to speed. While the three-pole relay is theoretically good, the single-pole relay serves the purpose because of that fact.

Speaking of the use of either the contactor or the circuit breaker, of course if you use contactors you will need the circuit breaker. If you can combine the two you save that much in first cost, but there may be added complication to your system. Where it is possible to use a circuit breaker, I have found it good practise to do so. The service I have in mind is not particularly severe, so that the carbonization of the oil is not the limiting feature at all.

W. T. Snyder: There is one point I want to mention about the open face controllers and starting contactors. As we know, they are now in disrepute in the steel mills on account of a certain amount of danger even on the low-voltage starters, not so much from shock, as from flashes and burns. The manufacturers have recognized this and have started to provide covers for them.

I noticed in one of the switches shown by Mr. Simon there is no method of providing for lowering the oil tanks. That becomes quite a problem on the large size switches, containing several gallons of oil, located back in the switch cell—it is hard to get a couple of men around them to lift them down. It is a job to lower them, either to replenish the oil or to make adjustments to the contact. On our high-tension oil switches which have the oil tanks hanging underneath, we put a drain cock on the bottom. We first drain all the oil into a vessel and then it is easy to remove the tank.

Mr. Simon says: " The resistance has to be designed with a considerably heavier capacity, and in some cases requires even continuous carrying capacity on all points." It is not clear to me whether or not he means full load carrying capacity, but if that is his meaning, his ideas conform to my own along that line.

In regard to the coal hoist referred to in Mr. Brown's paper, I was wondering why he had two small generators to supply exciting current to his contactors and the fields of the other small generator, why one was not enough. I imagine it is because he would have a factor of safety of two.

E. S. Zuck: I think I can answer the question Mr. Snyder raised about the two generators. The characteristics of the a-c. hoist motor were such that it required about 18 volts to furnish the necessary excitation current. The other machine, the 220-volt machine, was for operating the solenoid magnet. It is out of the question to operate the solenoid magnet from a machine having 18 volts.

Mr. Brown makes a statement that in the case of a hoist the material to be handled is unlimited. This may be the case in a great many instances, but if I remember correctly the motor manufacturers were advised in this case that the capacity of the tower was limited by the crushing machinery and the capacity of the hopper. I believe after one hour's operation, starting with the empty hopper, the hopper would have been filled, even with the crushing machinery in operation, so that would have limited the capacity of the hoist.

The question of dynamic brake control for towers of this kind is one which has been successfully worked out in several cases and this is a notable one. I worked out the dynamic braking problem, and using d-c. motors the problem is somewhat simpler. The characteristics of the d-c. motor are pretty well known and for different motors are more or less the same. When you come to a-c. motors the characteristics are not likely to be the same at all. Each case requires careful consideration by itself.

In this present case in the scheme of control used, the exciting current is not varied, there is a constant excitation on the motor used, and the control is obtained by varying the resistance. In this case I would like to call attention to the fact that the motor manufacturers gave values for the amount of magnetic resistance to be used in the rotor circuit, and so far as I know those were not changed by the control manufacturers.

Another point which may be brought out is that there is always a certain amount of resistance left in the rotor circuit, and that the rotor circuit cannot be short-circuited when lowering under dynamic control. There is a definite limit beyond which you cannot go without running risk of losing control and dropping the bucket.

W. T. Snyder: The gentleman did not get my question correctly. Mr. Brown said: "A small motor-generator set is located in each half of the engine room, supplying 220 volts d-c. from a 6-kw. shunt-wound generator for the coils of the contactors on the hoist and rack controllers." I take it from that that he has two of the generators, one on each half of the hoist, and I was wondering, if that is the case, why he had two of them.

E. S. Zuck: One generator is a 220-volt machine, while the other is an 18-volt machine. The 18-volt machine supplies excitation for the a-c. hoisting motor, while the 220-volt machine supplies the current to operate the contactor.

Raymond E. Brown: There are two motor-generator sets, one on each side of the plant. In the motor-generator set are a motor and two generators. This seems like a useless duplication of material, but in the design of this hoist the idea carried out throughout was to have two completely independent units, either of which could operate all of the devices. This idea was carried out from the point where the wires entered the building. We separated everything on the first floor into two circuits, everything being separated from that point up. This was done to make an economical plant for operation on half capacity, as well as to prevent the breakdown in any one piece of apparatus being able to shut down the entire plant.

G. E. Stoltz: Mr. Lankton brought out the point of the relative action of the relay at different frequencies. There might be something else besides the frequency in the secondary that affected its action. In starting up a rolling mill, the bearings are sometimes tight and the relays are probably adjusted to take care of a rather heavy starting condition. As the mill is brought up to speed the bearings gain their lubrication, so that the mill accelerates much more rapidly as it approaches full speed. This mill may have been at practically full speed before the last contactors had time to come in.

There has been considerable discussion of oil breakers, particularly those shown on the lantern slide by Mr. Simon, which are used on rolling mill drive. I believe he explained that this breaker was used on a 1000-h.p. rolling mill. We are coming to that in the application of hoists. Of course, the circuit breaker and contactor both have their own line of application. The mechanical construction of the oil breaker is not adapted for frequent closing. In rolling mills where the starting and stopping only takes place a few times a day, naturally the oil-breaker can withstand such service. But if it is necessary to run the mill back and forth, it is severe on the breaker, and it is necessary to put in an air breaker to take care of that condition.

W. O. Lum: Mr. Simon showed the position of the oil breakers as one for forward, another for reversing, and still a third for applying the direct current for braking. He also brought up the fact that this installation was made practically five years ago, and naturally cannot be fairly compared to present practise. Since that time it has been practically adopted as standard to plug the motor; in other words, reverse it, in order to bring it to rest, instead of applying d-c. voltage. Direct-current voltage for braking has worked out very successfully on the hoist that Mr. Brown has described, but other cases of application require study, as there are certain stresses set up by the direct current which we were not fully aware of in rolling mill practise.

Mr. McLain brought out a point in reference to added complication by using d-c. operated 220-volt switches on the hoist Mr. Brown described. I doubt very much if the addition of the 220-volts, and this other unit that generates the power, will cause failure or shut down any more frequently than if those switches were operated from the alternating current which is supplied to the motor. Direct-current operated switches are better developed and have been in the field a greater number of years than a-c. operated switches, so that we can depend on them to a greater extent.

As to the application of the bridge or coal unloader, there is no doubt but what that will give fewer interruptions with the d-c. than with the a-c. operated switches. I have in mind one case where an attempt was made to install a full automatic a-c. hoist. I do not think its success has been nearly so great as it would have been if the switches had been operated by direct current.

C. D. Knight: I do not mean to state that alternating current is as flexible as direct current for all applications, but I do say that a-c. contactors as manufactured today are just as reliable as d-c. contactors.

W. O. Oschmann: Last year at the Detroit Convention a description of a six-speed concatenated a-c. motor was presented. This control has seven triple-pole low-voltage contactors, one double-pole low-voltage contactor, two triple-pole high-voltage contactors and two single-pole low-voltage contactors. The oil switch equipment consists of one triple-pole circuit breaker, six hand-operated triple-pole single-throw oil switches and one double-pole single-throw oil switch. It is quite a complicated control. It has been in operation about two years, and in that time has developed very little trouble the most serious interruption being due to a broken control wire, which delayed the mill a short time. This outfit is not handled by an electrical man. The engineer operating a Corliss engine in the immediate vicinity also starts and stops the electrically-driven mill; he also manipulates the oil switches to secure the various speeds desired at the mill rolls. In the time that this plant has been in operation it has clearly shown that if the interlocks and control equipment are taken care of in a manner similar to d-c. apparatus, the results will be equally as reliable. The contactors and interlocks are examined each week, cleaned, and kept in good repair, the whole equipment is cleaned by compressed air each week, and the results obtained on this mill indicate that the reliability of a-c. control equipment is as good as the d-c. equipment, even if the a-c. equipment is more complicated.

G. E. Stoltz: I ask if the control on a rolling mill is not probably started more than once an hour; in other words, is not the operation of the switches about five per cent what it would be in the case of hoisting operations carried on continuously?

W. O. Oschmann: The operation of a mill depends greatly on whether there is trouble at the rolls. There have been cases where this mill has started and stopped repeatedly for several hours, also it has been maintained at a very low rate of speed for an hour at a time. In ordinary operation the mill may start and stop four or five times a day. At other times it may have four or five starts and stops in two or three minutes time. It is a rolling mill proposition.

G. E. Stoltz: There is hardly any comparison with a hoist.

W. O. Oschmann: It cannot be compared with a hoist.

J. D. Wright: There are many tables and other auxiliaries at the Gary mill which are operated by a-c. control, where no trouble has developed due to the use of alternating current rather than direct current.

Mr. Oschmann made the remark that in opening a three-phase circuit, with a three-pole contactor, arcing was observed on only two of the poles. I think that is probably due to some improper adjustment, and there is no question in my mind that a three-pole contactor would be better for opening a three-phase circuit than a double-pole.

W. O. Oschmann: In reply to Mr. Wright, I would say that the arc is not on the same two poles each time, it may be on any two of the three poles. It seems to depend on what part of the cycle the switch starts out.

J. D. Wright: Is it possible the current is passing through zero on one of these poles?

W. O. Oschmann: Possibly that is the reason.

C. D. Gilpin: I have been much interested in Mr. Brown's description of the a-c. unloading tower, as I had considerable experience some years ago with some a-c. dynamic braking coal handling bridges. On these bridges the controllers and motor-generators very much resembled those described by Mr. Brown, except that no separate contactors were provided for dynamic braking and consequently the control when lowering was not particularly accurate. These bridges were provided with 220-volt, 25-cycle mill motors and it was our endeavor to make the equipment as near the equivalent of a d-c. outfit as was possible. We found, for instance, that owing to the poor characteristics of the a-c. motor for trolley service it was necessary to increase the size of the trolley motors considerably over what would be required for direct current. The cost was considerably greater than that for a d-c. equipment of equal capacity, and we estimated roughly that it would have cost but a very few thousand dollars more to install a synchronous converter station. As great nicety of control, however, was not necessary, the a-c. system was probably preferable in this case.

The question of cost in plants of this nature is one over which there is sometimes considerable confusion. For instance, a number of d-c. machines equipped with expensive mill motors and provided with a substation are often compared as to cost with a-c. machines which are operated by the ordinary open type of wound-rotor induction motor, which is hardly fair to the d-c. system. In a plant such as Mr. Brown describes, however, where the peak loads are very high and a substation would have to be quite large in comparison with the mean current used, alternating current is undoubtedly a very attractive proposition.

While agreeing with Mr. Brown that the single hoist motor with clutches is cheaper than the type of hoist in which each of two independent drums is operated by a separate motor and controller, yet it would hardly seem possible that operation by means of clutches can be faster and less complicated than where independent motors are used. In the former system there are two master controllers and four air valves to be handled, while with the latter scheme, in which solenoid brakes are mounted on the motor shafts, there are three master controllers and one air valve to be manipulated, making two less pieces of apparatus. Moreover, with the independent drum arrangement each mechanism is reduced to its simplest elements, *i. e.*, a drum, the necessary gear reduction, a motor and a solenoid brake. The wear on the latter is quite slight if the dynamic braking is effective. The independent drum drive, however, is certainly more expensive in first cost, and therefore in certain cases it is undoubtedly better engineering to install the clutch system.

Arthur Simon: Mr. Whiting compares the oil-break switch with the air-break switch, and says that the air-break switch is more reliable. I think that Mr. Whiting has compared his newest air-break switch with the oil-break switch which he discarded, because as I pointed out in my paper, there is one oil-break switch operating on a rolling mill which operated 50,000 times with the oil just as clear, apparently, at the end as it was when it was put in. I also know of a large installation that has an oil-break switch which has been in service for several years, and the oil in one instance was not renewed for one and a half years. Of course, it is necessary once in a while to replenish the oil.

As far as inspection is concerned, I do not believe that any operator would stick his nose into the air-break switch while it is operating. In such case you have to open your circuit-breaker, and you may just as well lower the oil tank and look at the contacts. There is no doubt that the contacts of the air-break switch must have more metal than the contact of the oil-break switch, and as that is copper, it is more expensive and the weight of material is greater. If the oil switch, on the other hand, is properly constructed there is practically no spilling of the oil, so that the replacing of the oil is a small item, provided the switch is constructed so that the carbon deposits settling on the bottom are not stirred up every time the switch operates.

Mr. Albrecht spoke of the relative value of the three-phase and single-phase relays in the secondary circuit, if I understood his remarks right. I pointed out in the paper, or tried to point out, that the three-phase relay, because it gives a constant pull for a constant effective current, is independent of the frequency. On the other hand, it is not possible to get a constant pull on the single-phase relay, because it is not possible to get phase displacement of 90 degrees between the flux interlinked with the main coil and shading coil. Therefore, there is a pumping action when the frequency in the secondary is low.

One of the speakers mentioned a particular installation where the acceleration was very rapid towards the end, when the motor was at high speed. I believe that is due to this cause—if relays of the single-phase type were employed this could not be avoided by any adjustment, because an adjustment which is correct for high frequency is not correct for low frequency.

Mr. McLain said the jamming relay did not prevent strain on the operating parts. He modified that and said it would prevent the strain only in a degree. If that degree is sufficient, the jamming relay does all it is intended for. If you use several jamming relays, you can prevent any serious strain on the parts. There are certain installations where the jamming relay performs another purpose, take the electric shovel and other similar installations like that. It is possible for the shovel to strike solid rock while the motor is running at full speed. Then the motor would be stalled with the resistance short-circuited and the torque which developed at that point would probably not be in excess of the normally rated torque of the motor. If we have a slip clutch only and no jamming relays, the clutch will slip while the motor is slowing down, and will hold on again as the motor reaches lower speed and the torque is decreased again. The jamming relay prevents the motor from going beyond the breaking-down point. That is an important application of the jamming relay, and as far as I know, the jamming relay is the only device that will do that. We have slip clutches on that installation, also.

I think Mr. McLain has misunderstood the connections of the three-phase relay. That relay, as Mr. Kennedy has pointed out, does not need to beat the switch which it controls. That the current peaks on the 1000-h.p. motor which I show are decreasing is merely accidental. As a matter of fact, the last peak, as I remember is the second highest of the whole cycle. The advantage of the individual series relay is, as I pointed out, the adjustment of the various relays for different torques. In most cases we adjust them for increased torque, increasing torque with the motor speed on centrifugal pumps, and also on excavating machinery. This particular instance was exceptional. Furthermore, the relays are not energized when the primary circuit of the motor is closed. They are energized in succession as the different clappers are cut out and the resistance decreases. That is clearly shown in diagram Fig. 13.

Mr. McLain also criticised the use of d-c. contactors on coal bridges where d-c. is used for dynamic breaking, on the ground that it would add to the number of links which might stop the equipment. The most important thing on the hoist is to prevent the load from overhauling the motor, in other words, to prevent the bucket from dropping. That is the reason why we put in direct current for dynamic breaking. We would rather have the equipment stop with our d-c. supply, than to have it go on and hoist and give us no indication that we cannot lower our load with safety. So that the use of d-c. contactors in that particular instance, I believe, is an additional safety rather than a weakness in the method of control.

Mr. Knight has mentioned that a phase failure relay will be put on the market soon. There is one on the market already, which prevents not only failure of phase, both during running and during the standing still of the motor, but also protects against phase reversal.

Mr. Knight further says that the oil-type switch is a good one where infrequent operation is encountered. I have given some data referring to frequent operation of oil switches.

Mr. Knight also mentioned something about standardization. That brings me to a subject which I have had in mind for many years, but I always ran against a stone wall. That is at least the approximate standardization of secondary currents and voltages. The operating men here know that when they ask for a control equipment for an a-c. motor they always have to specify the secondary current limitations. If our motor friends could get together and standardize secondary voltages within certain limits—we have to allow some leeway to the designer—matters would be helped a good deal, I believe. I have made an attempt in that direction on various occasions, as long ago as ten years, but nothing ever came out of it. Perhaps I was wrong in my ideas.

Mr. Oschmann spoke of the expensive current transformer in the secondary circuit. As a matter of fact, while it is possible to use a transformer in a secondary circuit, we have not yet encountered any case where we had to actually use it. It was always possible to get a series relay directly into the secondary circuit, and this is much more desirable, because a relay on ordinary accelerating service always forms neutral form of the resistance, and therefore has, when it is in circuit, practically no voltage to ground. As regards the bulkiness of the transformers, they would mostly run at low frequency, and the iron induction can be high.

President Lincoln also mentioned the use of single-phase secondary relays in contrast with three-phase relays. I have answered that point. It is significant that in some installations where single-phase series relays were used for all of the accelerating points, it was found necessary to use three-phase relays for the last step, which supports the point I make in regard to the frequency affecting the sensitiveness.

Mr. Snyder mentioned some means for lowering the tank used for the oil switches. I believe that most of the oil switches of medium and large capacity today are equipped with such lowering gear, at least they ought to be.

When I spoke of the capacity of resistance in the particular case, which Mr. Snyder mentioned, I contrasted the reversible automatic speed regulator with the non-reversing starter. The resistance has to be figured the same way, taking into consideration the duty cycle, as it is done on direct current.

Mr. Stoltz also spoke about the oil breaker not being adapted for frequent closing. I have answered that point.

With regard to the plugging of the motor for quick stopping, there is always the danger that the operator throws his control handle over to full speed, reverse, and then leaves the equipment alone, expecting it to stop the motor. We have the same trouble as before, so in some cases dynamic braking by d.c. may be desirable. I have noticed lately that it has been specified by the mill, so that while the particular installation I described is several years old, there seem to be some operating men who still believe in that method of motor stopping.

The necessity of using a three-pole switch for opening a three-phase motor circuit or reversing it has been mentioned. It seems to me there is no more reason for using a triple-pole switch for opening a three-phase motor than there is for using a double-pole contactor for opening the circuit of a d-c. motor. We often use a contactor only on one side of the line in the case of direct-current, and we get the same factor of safety if we use a double-pole contactor on a three-phase or three-wire circuit in alternating-current.

Raymond E. Brown: When Mr. McLain introduced the question of the advisability of using series or parallel grouping of the resistance, that is, in adding additional steps in parallel or by cutting out the steps in series, I thought possibly we would find out the reason for the use of these two methods in different cases. In buying equipment for about fifty coal and ore handling bridges in the last ten years, our firm has been interested in trying to find out why the resistance varies so much in different cases. We are very much interested in the weight of the equipment, as in designing a trolley bridge the weight of the electrical equipment on the trolley is an important factor in getting at the weight of the bridge and its cost. Each pound of additional weight in the trolley means three pounds of additional weight in providing the span.

We have so far been unable to find any real uniformity in the weight of resistance in consecutive jobs of about the same size and voltage. Manufacturers seem to vary this a great deal, and one time will offer a control with resistances grouped in series, and another time in parallel, with a wide variation in the weights.

Referring to the question brought up this morning about the material for the bridge, I hoped to hear some one speak of the new material which was recently called to our attention in the shape of an alloy which is rolled or drawn into the girders. According to the claims of the manufacturer, it will do away with most of the disadvantages of cast iron. It is lighter, and the material for the entire drum could be one continuous piece, no joints between the separate bridges, merely doubling on itself and bending around the mounting rope. Outside of the circular and one visit of their representative we know nothing about that, and there may be other reasons why it is not being considered.

It is usual for steel mills to say they will use resistances with a rise of temperature of 100 degrees or 200 degrees, or any other amount you choose; but the poor manufacturer who is designing the machinery to be sold on a competitive basis has to deal with the purchasing agent, who very frequently tabulates his bid on the basis of total weight and total price, and apparently decides them on the basis of price per pound. Under these circumstances it is hard for the crane or bridge manufacturer to introduce many refinements which would be undoubtedly of great advantage to the operator if they were installed. Many times we find after the machine has been in operation for some time that these refinements are put in by the users of the machinery, whereas we were unable to obtain any recognition of their value when the machine was first supplied.

With reference to the criticisms about my statement as to the advisability of a large motor for hoisting, the statement made by Mr. Bright would be correct on a hoist where the lift was low, and the time of hoisting was small in comparison with the time for closing. In the particular hoist described, the height of hoist is 90 ft., and as we were able to design it with a large leeway at the top, the operator was able to let the load coast to a stop in the majority of cases.

With reference to the question of limiting switches, and the advisability of using the geared limiting switch, it seems to me that the desirability of the geared limiting switch as against one operated by the load itself depends, to some extent, on the organization of the mill. In the particular hoist I described, it is cared for by one department which operates and repairs it. In other mills the crane is operated by one department and repaired by another. I think in the case of a bridge or hoist it is entirely possible that one department will replace the ropes, while the geared limiting switch, being an electrical device, is outside of their jurisdiction, and consequently is not changed. We know of cases where a new rope was put on a bridge, the geared limiting switch not changed. The new operator coming on the next shift knows nothing of the change having been made, and proceeds to hoist the bucket into the drum. In the case where the repairing is done by one department, and the operating done by another department, the geared limiting switch does not appear to be desirable, but the style of limiting switch operated by the dump or skip should be used.

An address delivered at the Annual Meeting of the American Institute of Electrical Engineers, New York, May 18, 1915.

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HOW BELL INVENTED THE TELEPHONE

BY THOMAS A. WATSON

IT IS my privilege and pleasure to speak to you of the invention of the telephone, with which event it was my good fortune to be connected, my association with Prof. Bell as his mechanical expert having brought me into close touch with nearly all his experiments both before and after his great discovery.

I shall try to tell the story as it impressed itself on my mind in those early days when I was a young man of about 20, just out of my apprenticeship as a maker of electrical apparatus, intensely interested in my work, and with a full share of youthful enthusiasm. In my story, I shall not use the terms and formulas of modern telephony, for they would certainly be out of place in speaking of the time when that science, now so complex, was contained in one human brain.

It was in the year 1875 that the telephone emerged from the mists of the unknown into a world that had no dynamos, no electric motors, no trolley cars, no storage batteries, no electric lights, no wireless telegraphs, no steam turbines, no gas engines, no automobiles, and no professional electrical engineers, for none of our universities had up to that time offered to their students electrical courses.

Those men we all revere—Davy, Faraday, Henry, Volta, Oersted, Ohm, Maxwell, Thomson, and others, had already laid the deep and sure foundations on which modern electrical practise has been built, but apart from the telegraph, electricity, as a practical utility, had scarcely entered the daily life of man.

In 1874 in place of the great electrical manufacturing establishments of the present day, there were a few crude little work shops scattered throughout the country, eking out a precarious existence chiefly by making telegraph instruments, school apparatus, call bells, annunciators, etc., and also experimental apparatus for the many inventors who utilized the meagre facilities of those shops to put into practical shape their electrical projects. This was an important feature of the electrical activities of that time, for although the work of these men was for the most part obscure and unfruitful, they were undoubtedly the leaders in the great awakening to the practical possibilities of electricity that began about the time of which I am to speak, and which has since then produced such tremendous results.

In 1874 I was employed as a mechanician in one of the most important of these shops in the United States. It was in Boston, owned and operated by Charles Williams, trained as an apprentice of that famous electric antique, Daniel Davis. Williams, when he was very busy, employed about fifty men, but while I was with him his works seldom ran at more than fifty per cent of their normal capacity. His tools were almost entirely hand lathes. His shop possessed no milling nor screw machine nor had it even a metal planer. Practically all his work was done on hand lathes or with the vise and file. He had one 16-inch engine lathe, to operate which was the highest earthly aspiration of his apprentices. It wasn't in good condition, for one of the boys had run a boring tool into the hole in the spindle so the live center wiggled badly, but we managed to do some rather difficult and accurate work on it in spite of its defects.

Into Williams's dismal and poorly equipped shop Alexander Graham Bell came, in the year 1874, to get his "harmonic telegraph" invention put into practical shape. J. B. Stearns had just then perfected the "duplex telegraph" which would send two messages simultaneously over a single wire. Prof. Bell was sure his invention would send at least six or eight. My work at Williams's at that time had become largely making experimental apparatus for inventors and I am glad to say that Prof. Bell's work was assigned to me.

Prof. Bell was very enthusiastic over the possibilities of his telegraph on which he had been studying ever since his arrival in the United States in 1872. Its operation depended, as you know, on the fact that a stretched string or a tuned reed will be set into vibration when impelled by a succession of impulses corresponding in number per second to its pitch. Here is one of Bell's telegraph receivers. It is a simple electromagnet with a strip of steel clamped to one of its poles, having the other end of the strip free to vibrate over the other pole. The transmitter had the same parts with the addition of contact points that kept its steel reed vibrating when the current was connected and, making and breaking the main circuit at each swing, sent an intermittent current pulsing into the line and through the distant receivers. Each receiver reed was expected to respond to impulses of its own pitch and to ignore those of any other pitch.

I made for Prof. Bell six or eight of these transmitters with their reeds tuned to different pitches and the same number of receivers with their reeds tuned to correspond. Their test, however, gave results sadly out of accord with his expectations and a long series of experiments followed with rather unsatisfactory results.

The saying so frequently offered for our consolation: that we profit more from our adversities than we do from our successes, was certainly applicable to Prof. Bell's case at this time, for had the rhythmic intermittent current that actuated his telegraph accomplished the result he expected and brought him fame and fortune, he might not have been impelled to seek a better form of an electric vibration and so might have missed the discovery that has since placed his name among the immortals.

Prof. Bell's experiments with the apparatus I made for him soon revealed the serious defects of the intermittent current wave. He was able to transmit with it two or three messages, each on a different pitch, with a reasonable degree of certainty, but when a greater number was attempted, the added series of impulses seemed to fill the gaps in the other series and produce practically a continuous current, causing serious interference between the messages. The need of a better form of an electric wave was apparent; making and breaking the circuit so many times a second seemed but the first step in the development of his idea. The fact is, Bell had had for a year or more a clear conception of the sort of current he needed, one undulating in waves which would be the exact equivalent of sound vibrations, although he had as yet devised no satisfactory means of producing such a current. An electric current undulating in true wave form would not, he believed, smooth out into a continuous current when several series of impulses were superposed but would keep its wave form through all the complexities that might be impressed upon it. Many sounds can traverse the same air without confusion, so, he thought, such a system of electric waves having the mathematical form of sound waves in the air, might transmit an indefinite number of pitch series on a single wire, to be selected and resolved into separate messages by his tuned receivers.

Bell also foresaw that the apparatus which could generate and transmit such true electric waves might also solve another great problem he had been dreaming about.

One must imagine a world in which the telephone was absolutely unknown to appreciate my feelings when one evening during the course of some experiments on his telegraph apparatus, Bell told me he had an idea by which he believed it would soon be possible to talk by telegraph. He put his conception into the words of his famous formula which I then heard for the first time: "If," he said, "I could make a current of electricity vary in its intensity, precisely as the air varies in density during the production of a sound, I should be able to transmit speech telegraphically." Some practical mechanism to produce such a current was the goal to be striven for, he asserted. He then described to me what he called his "harp telephone," a complex affair having an elongated electromagnet with a multiplicity of steel reeds tuned to many pitches and arranged to vibrate in proximity to its poles; as if the magnets of a hundred of these receivers were fused together side by side. These reeds might be considered as analagous to the rods in the harp of Corti in the human ear. It was Bell's first conception of a speaking telephone. His idea was that a sound uttered near the reeds would cause to vibrate those reeds corresponding to both the fundamental tone and to the overtones of that sound. Each reed would generate in the magnet an electric wave all of which would combine into a resultant complex wave. This passing through a similar instrument at a distant station would, he imagined, set the same reeds into motion and so reproduce the original sound. He had even considered the possibility of using a single reed actuated by a parchment diaphragm over an ordinary electromagnet. He had not had either of his conceptions constructed for he was sure that electric waves generated in this way would be too feeble, to be of the least practical value. His harp telephone, however, was a favorite idea with him and he often spoke of it to me. It was never constructed probably on account of the expense, but with this clear conception in his mind, of the possibilities of a true electric wave, struggling for practical expression, Bell continued his work on his harmonic telegraph trying to attain a result clearly impossible with a transmitter that merely made and broke the circuit.

I am afraid that my attitude towards Bell's telegraph, after several months' work on it, had become one of disgust with its perversities, and hopelessness as to its future. Its operation was so uncertain and baffling that I remember that even Prof. Bell himself began to lose his enthusiasm. His confidence in the intermittent current was vanishing and means for generating his better waves had not arrived. But, "when half gods go, the gods arrive," and this time of depression and disappointment was the right preparation for the new development that was close at hand.

In the attic of the building 109 Court street, Boston, where Williams's shop was, two rooms had been partitioned off and used by Williams for the manufacture of tin-foil condensers. These rooms Bell used as his laboratory at that time. Those rough attic rooms, freezing in winter and unbearably hot in summer, had witnessed many discouraging experiments with the harmonic telegraph with a few slight successes, but on the afternoon of June 2d, 1875, something came to light there that certainly was a recompense for all previous troubles. A slight derangement in the telegraph apparatus gave an opportunity for the great idea that had been incubating in Bell's mind so long to break through its shell.

On that afternoon Bell was in one of the rooms tuning the receivers, an operation they constantly needed. He had a novel way of doing this that he had originated and which had become a habit with him. When he was trying to bring the pitch of a receiver reed into accord with that of its transmitter, he would press that receiver reed against his ear. He could then hear the nasal drone of the intermittent current coming from the transmitter in the other room and by changing the length of the receiver reed he could adjust its pitch to correspond with that tone. It is interesting to note that when one of his harmonic receivers is used in this way, it becomes a close analogue of a modern telephone receiver, as the edges of the ear clamp the free end of the spring and so damp its natural rate of vibration and cause it to vibrate as a diaphragm.

On the afternoon of June 2d, 1875, Bell was doing this with one of the receivers and at that very moment I happened to snap the steel reed of another instrument in the other room connected into the same circuit, which for some reason was not vibrating as it should, and needed that physical stimulus to start it. It did not start at once so I gave it several vigorous plucks, undoubtedly expressing my opinion of the thing in vivid shop language, when I heard a commotion in the next room and out Bell came in great excitement to see what I had been doing, telling me that he had heard in the receiver at his ear the unmistakable timbre of the sound of one of the reeds. His excitement came from his realization that he had heard the first real sound that had ever been transmitted electrically. It needed but a slight examination of the apparatus to reveal the fact that the steel reed I had snapped, magnetized by its long use in connection with magnets, was functioning as a magneto-electric generator and by its vibration had generated in its magnet an electric current that was moulded into undulations exactly analogous to the sound waves of the plucked reed. That such slight means could generate a current not only strong enough to be heard in the receiver but actually to set into visible vibration the reed of another receiver in the same circuit in Bell's room, was a revelation to him. He saw at once that he had been wrong in thinking that the vibration of a steel reed could not produce electric waves of any practical value and that here was the solution, not only of his harmonic telegraph but also of his speaking telephone. He realized immediately that the apparatus that could generate, transmit and receive so efficiently one sound with its fundamental tone and with its overtones could undoubtedly be made to do the same for any sound, even speech itself. The gods had arrived, bringing new enthusiasm and hope; even my gloom was dispelled. We spent the rest of the day repeating the experiment by snapping many different sizes and shapes of steel springs and tuning forks over magnets with the same surprising result and before we parted that night Bell gave me directions for constructing the first speaking telephone. He knew that the diaphragm of the Scott phonautograph when impelled by the vibrations of sound would impress them on the recording style attached to it; why then would not such a diaphragm actuated by the voice, force the steel reed of one of his receivers to follow the vocal vibrations and cause it to generate electric waves with the form of speech waves? Following this thought to its conclusion, Bell sketched out the first speaking telephone the world has ever seen and gave me directions for its construction. I was to mount one of the harmonic receivers in a wooden frame, attach the free end of its spring to the center of a tightly stretched parchment drum head, also mounted in the framework, and provide a mouthpiece to concentrate the voice on the other side of the drum head.

I did this the next day. Here is a replica of it. All that is left of the original is now in the National Museum at Washington. My recollection is that I had this first telephone ready for testing the next day, June 3d. It had many defects. The diaphragm was delicate and easily torn and as it absorbed the moisture of the breath required constant tightening, but it transmitted to my ear over a wire about 200 feet long, running from the fifth story of Williams's building to my work bench on the third story, the unmistakable timbre of Prof. Bell's voice in a few imperfect words, using for listening one of the harmonic telegraph receivers through which Bell had made the discovery. It was a meager result and a bitter disappointment, for I, at least, and, I fancy, Prof. Bell too, had anticipated a much greater conversational fluency even in that first telephone.

I have noticed that one's mental attitude towards a phenomenon changes as the novelty wears off. The new effect does not seem so wonderful after a few repetitions. This is perhaps the reason why my memory tells me that during the months immediately following the discovery that magneto-electric waves generated by a vibrating steel reed were strong enough for practical use, the telephone seemed to grow poorer in its operation instead of better. Bell carried on many experiments for which I made the apparatus, with the purpose of increasing the strength of the new wave not only for its use in his telegraph but also in his telephone. He felt that any improvement applicable to one invention would also help the other. His work for some months was devoted to the telegraph as well as to the telephone, for his friends and financial backers were all strongly of the opinion that it was much wiser for him to devote himself to a real practical thing like the telegraph rather than to such a chimera as the telephone.

Progress was over the same desert road with a few green spots that inventions seem prone to travel on and it was not until March 10th, 1876, nearly ten months after its birthday that the telephone transmitted its first complete sentence. Though not so noble as the first sentence that Morse telegraphed from Washington to Baltimore a few decades before, "What hath God wrought," still the telephone's first sentence had a certain homely practicality about it that clearly takes it out of the category of the frivolous. It was, "Watson, come here, I want you," uttered by Bell from his laboratory to his bed room in the boarding house, number 5, Exeter Place, Boston. I am sure that I went at once. Commonplace as it was, the sentence seemed to break the spell and the telephone progressed after that by leaps and bounds.

I have here the wire over which that first sentence was sent. With a forethought that quite surprises me today, I took down this wire when the laboratory was vacated in 1877, inscribed it and put it into a safe where it remained until a year or two ago when I presented it to the American Telephone and Telegraph Co. for its museum. The inscription, which I wrote when I first took it down, is as follows: "This wire connected room 13 with room 15 at number 5 Exeter Place, Boston, and is the wire that was used in all the experiments by which the telephone was developed from the fall of 1875 to the summer of 1877, at which time the telephone had been perfected for practical use. Taken down June 8th, 1877, by Thomas A. Watson."

This was the year of the Centennial Exposition at Philadelphia and Bell decided to make an exhibit there of his inventions. He had me make for him some nicely finished telephones of the best forms that he had devised, including his first battery transmitter.

In June, 1876, Sir William Thomson, chairman of the committee on the electrical exhibits, with members of his committee, examined and tested Bell's apparatus. We have a valuable record of the impression the telephone made upon his mind in his opening address to the British Association, September 14th, 1876, wherein he said:

> I heard, "To be or not to be * * * * there's the rub," through an electric telegraph wire; but, scorning monosyllables, the electric articulation rose to higher flights, and gave me messages taken at random from the New York newspapers—"S.S. Cox has arrived" (I failed to make out the S. S. Cox), "The City of New York," "Senator Morton," "The Senate has resolved to print a thousand extra copies;" "The Americans in London have resolved to celebrate the coming 4th of July." All this my own ears heard, spoken to me with unmistakable distinctness by the thin circular disk armature of just such another little electromagnet as this which I hold in my hand. The words were shouted with a clear and loud voice by my colleague judge, Professor Watson, at the far end of the tele-

graph wire, holding his mouth close to a stretched membrane, such as you see before you here, carrying a little piece of soft iron, which was thus made to perform in the neighborhood of an electromagnet in circuit with the line, motions proportional to the sonorific motions of the air. This, the greatest by far of all the marvels of the electric telegraph, is due to a young countryman of our own, Mr. Graham Bell, of Edinburgh, Montreal, and Boston, now becoming a naturalized citizen of the United States. Who can but admire the hardihood of invention which devised such very slight means to realize the mathematical conception that, if electricity is to convey all the delicacies of quality which distinguish articulate speech, the strength of its current must vary continuously and as nearly as may be in simple proportion to the velocity of a particle of air engaged in constituting the sound?

Up to the summer of 1876 all the tests of the telephone had been made on indoor wires but soon after this convincing trial at Philadelphia, it became evident to Prof. Bell that his invention was ready for higher flights. Some preliminary tests on a real line in Brandford, Canada, in which the transmission was all in one direction, the return communication being by telegraph, were followed by a complete test of the telephone's practicability as a transmitter of intelligence between distant points under outdoor conditions. On October 9th, 1876, Bell and I carried on a long conversation over a real telegraph wire about two miles long running from Boston to Cambridge, Mass. Bell was at the Boston end, I at Cambridge. The telephones we used were those that Bell had exhibited at Philadelphia and were probably the identical instruments with which Sir William Thomson made his famous tests. In order to prove to a doubting world that the telephone could be accurate in its transmission, we made a record of that first conversation ever carried on over a real line and so it has been preserved. At the beginning of the test we were not able to make our voices audible to each other. The cause seemed to be the high resistance of a telegraph relay that I discovered in the circuit in another room in the Cambridge factory, for, after I cut that out, we were able to talk with the greatest ease, as the opening sentences of our recorded conversation indicate, which were:

"Bell: What do you think was the matter with the instruments?
Watson: There was nothing the matter with them.
Bell: I think we were both speaking at the same time.
Watson: Can you understand anything I say?
Bell: Yes, I understand everything you say.

Watson: The reason why you did not hear at first was because there was a relay in the circuit.

Bell: You may be right, but I found the magnet of my telephone touching the membrane.

Watson: I cut this relay out, and then the sounds came perfectly.

Bell: I hear every syllable. Try something in an ordinary conversational voice.

Watson: I am now talking in quite a low tone of voice.

Bell: The sounds are quite as loud as before and twice as distinct"—

and so on for more than a hour. This record which was published in the *Boston Advertiser* of the next day shows a surprising accuracy when the crudeness of those early telephones is taken into consideration.

I need go no further in my account of those days of struggle. The successful working out of the telephone, as in the case with all inventions, was a matter of endlessly considered detail. It was patient, plodding work with a few hours of intense excitement. Other tests were made later in 1876 on still longer lines, and in April, 1877, the first telephone line was constructed, four miles long, and the telephone installed thereon, beginning its competition with the telegraph as a practical business proposition.

Since then, what tremendous things have been done by the telephone engineers on whom the responsibility has fallen, of continuing the work so splendidly inaugurated by Dr. Bell. The work of these men during the 38 years that has elapsed since Dr. Bell's experiments on the telephone has been ceaseless, energetic, untiring, wise, and accurate in the highest degree. Telephone engineers have overcome one by one the multitude of obstacles that stood in the way of that high ideal—universal service, until today we applaud the latest achievement, under the able leadership of your incoming president—transcontinental telephony, the marvel of which has impressed itself deeply upon my mind all the more because Dr. Bell and I had the honor of formally opening the New York-San Francisco telephone line on January 25th of this year, as we opened the first telephone line, 2 miles long, between Boston and Cambridge, 39 years before. We talked over this line 3400 miles long (really 4400 miles, for its terminus was, during the most of the time, in Jekyl Island, Georgia) more clearly than we talked from Boston to Cambridge 39 years before. Amazing as this was, a climax of the wonders I had been participating in was reached when Dr. Bell switched in another telephone and said to me through it: " Mr. Watson, I am now talking through an exact duplicate of the first telephone made in 1875. Can you hear me?" I heard him perfectly, and when I explained to the audience at my end of the line just what was happening and repeated Dr. Bell's words, I was not surprised to see tears in the eyes of several of those hard-headed business men of California, for I myself was thrilled through and through with the thought of the immensity of the work that had been done since I made that first telephone for Prof. Bell and with my realization that this transcontinental line, stupendous achievement as it is, was merely a big incident in the life of the men whose brains have built up an organization almost incomprehensible in its size and scope, with its nine million telephone stations, making twenty-eight million telephone conversations each day over twenty million miles of telephone wires—that stupendous organization we call the " Bell system."

Even these figures are but part of the whole, for there are now in the world more than 14 million telephone stations, making 42 million conversations daily over 33 million miles of wire. We can but wonder at such a fructification in four decades of that virile conception of the man we today honor ourselves by honoring—Alexander Graham Bell.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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THE TREND OF ELECTRICAL DEVELOPMENT

President's Address

BY PAUL M. LINCOLN

AN ANNUAL address by the president of our Institute is more than a perfunctory affair. It is a constitutional requirement. It is enumerated specifically in our constitution among the duties of the president—"He shall deliver an address at the annual convention."

It has occurred to me that in my address on this occasion it might be well to trace the progress of some of the developments and practises that have marked the path that the electrical engineer has traversed in the past, with a view of obtaining some idea, possibly, as to whither these paths may lead us in the future. Insofar as this method incorporates a review of the past it presents no particular difficulty; but when it involves a prognostication of what a continuation along any particular line of development will finally lead to, it delves somewhat into the realms of prophecy. I realize full well that anyone who attempts to deal in prophecy among the inventions and developments of this day and age is running a grave risk, and I therefore do not propose to wander far from what I conceive that the trend of present development will carry us toward in the future.

In the matter of efficiency, it has always been recognized that electrical apparatus is in a class by itself. Mechanical energy can be converted into electrical by a generator, or *vice versa*, by a motor, at an efficiency ranging up to as high as 97 per cent, or even more in the most favorable cases. I think it is a safe statement to say that the average efficiency of the conversion of mechanical energy into electrical by generators, or electrical energy into mechanical by motors, including all sizes under actual operating conditions, will reach 90 per cent. There are, of course, many cases where the efficiencies are lower than 90 per cent. On the other hand, there are many cases where the conversion is carried on at much higher efficiencies, and I believe that the assumption of 90 per cent as an average figure is not far from the truth. Owing to the fact that the size of the average electrical generator is much greater than that of the average motor and that it is possible to operate the generator at higher average loads than in the case of the motor, it must be apparent that the average efficiency in converting mechanical energy into electrical energy is higher than in the reconversion of this electrical energy back into mechanical. The average generator efficiency is undoubtedly well above 90 per cent, while it is doubtful if the average motor reaches so high a figure. However, the general conclusion I would draw from these figures is not modified by this difference between generator and motor. This conclusion, which must be apparent to anyone, is that no development of a revolutionary character can be looked for in this respect. Our ability to convert mechanical energy into electrical, or *vice versa*, has reached so high a value that even if we could obtain perfection itself we could add only a matter of 10 per cent to what we have already accomplished. This conclusion must hold unless the law of conservation of energy is revoked, and I am not predicting any suspension of that law.

When we come to deal with the efficiencies by which electrical energy in one form is transformed into electrical energy of another form, efficiencies are found to be still higher. The efficiencies of some of our larger transformers, for instance, exceed 99 per cent. The synchronous converter, in which alternating current is changed into direct, attains efficiencies approaching 98 per cent. It is evident that perfection itself could not add greatly to existing performances and hence nothing revolutionary may be expected along this line in the future.

When we come to consider the prime mover, we find a marvelous improvement in recent years. Taking up first the waterwheel, the early attempts to develop power at Niagara Falls constitute a significant commentary upon the status of the waterwheel at that time (the late 60's and the early 70's). About that time the building of what is now known as the Schoellkopf canal at Niagara Falls made available a head of about 215 ft. at the edge of the cliff below the falls on the American side. Of this 215-ft. head, these earliest wheels used only some 15 or 20 ft. for some of the least progressive, and from there up to possibly 40 or 50 ft. for the more progressive. After passing through the wheels under this head, the water was then discharged at the face of the cliff and fell uselessly for the remainder of the distance, much to the detriment of the scenic beauty of the bank. And not only was it impossible at that time to obtain waterwheels that would work under more than these very limited heads, but the efficiencies of such as were used were very far below those attainable now. Today, waterwheels have no limit in head, except that imposed by the strength of available materials, and efficiencies ranging up to 90 per cent are expected as matters of course. Improvements in waterwheel design will, of course, continue, but perfection itself would add but a matter of 10 per cent to the best of our modern practise, and not to exceed 20 per cent to 25 per cent to the worst. Therefore, in waterwheels, as well as in motor and generator practise, we are approaching the limits set by natural laws almost as closely as human ingenuity can be expected to attain. No startling or record-breaking developments need be expected along these lines so long as the law of conservation of energy holds.

In thermodynamic engines too, the last few years have seen marvelous improvement. The reciprocating engine of Watt has largely given place in recent years to the steam turbine, and the use of the turbine has enabled us to attain efficiencies in thermodynamic conversion that were out of the question with the reciprocating engine of Watt. In the thermodynamic conversion the law of conservation of energy takes a peculiar form. No conceivable method of thermodynamic conversion can begin to transform all of the energy contained in a lump of coal, for instance, into dynamic or mechanical form. If the heat contained in the coal is used to heat a fluid and that fluid is used in a thermodynamic engine, the maximum mechanical energy that can be taken from that engine can bear no greater ratio to the total heat imparted by the fuel to the fluid than the actual range of temperature used in the engine does to the maximum absolute temperature of the fluid as it enters the engine. The efficiency which would result by the use of this ratio of temperature ranges is that which would result if what is known as the "Rankine cycle efficiency" were 100 per cent. Some of the best of our modern steam turbines have attained to as high as 75 per cent—or possibly a little more—of this Rankine cycle efficiency. In these most perfect engines, therefore, perfection itself would not add more than 25 per cent or such a matter. It should be particularly borne in mind that this statement is true only of the best of modern practise. It is not true that the average of modern practise attains anywhere near this degree of perfection. It is only with prime movers of the largest size and most modern design and construction that so close an approach to the ideal can be attained. As capacity is reduced it becomes rapidly more and more difficult to attain the higher degrees of economy in thermodynamic machines. This must always remain one of the potent factors in the economics of power supply. It is, and undoubtedly always will be, one of the fundamental reasons why central station supply of electric service must prevail as against isolated plant supply for the same service. The central station can, of course, use units which are very large in comparison, and can be worked at much higher average loads than must necessarily be the case with an isolated plant.

One obvious means that has been suggested to improve the efficiency of the thermodynamic engine is to increase the temperature range through which the working fluid is used. When using water or steam as the fluid in our heat engine, there are certain practical limitations to the temperature range which is available and the temperature range cannot be materially extended over the best of modern practise. The only two ways to extend this temperature range when using steam are to increase the superheat or increase the pressure. Increasing the superheat over the best modern practise does not promise results commensurate with the expenditure of heat to obtain this superheat, since increasing the temperature at one end of the heat cycle simply involves a loss in the efficiency at the other end. There is a rather definite limit to superheating of steam beyond which it is useless to go. Increasing the steam pressure does promise results, and it is probable that the tendencies for the future developments in thermodynamic engines will be toward these higher steam pressures.

Another promising method of increasing temperature range is that to which attention has been called during the last year or two by Mr. W. L. R. Emmet of Schenectady. He has called attention to the advantages of using mercury as the working fluid in a heat engine for temperature ranges above those available with steam. After working the mercury through a given temperature range, the heat remaining in the mercury is transferred to water and the steam thus made available is again worked through a lower temperature range. The advantages of this are that the steam is in practically all respects the same as in standard steam turbine practise and the mercury cycle is closely similar to the steam. Additional energy is made available from the same amount of initial heat, due to the greater temperature range obtainable by the use of the mercury. The main disadvantage is the poisonous nature of mercury vapor and the difficulty of absolutely preventing its leakage at the high pressures and temperatures of the mercury boiler. These practical difficulties make it too early to predict whether or not this method will work out as a feasible solution of the thermodynamic engine problem. However, it can be said that without some such method or device, the future is apt to bring no revolutionary improvements in thermodynamic engines over the best of modern practise. Improvements of course will undoubtedly continue to take place, but it cannot be hoped that the improvements of the future will be of the same revolutionary character as the improvements in the thermodynamic engine which have taken place within the last 10 or 15 years. Here again we are approaching so close to the law of conservation of energy that it is safe to make a prediction of this nature.

In the matter of size and capacity of generating units, it can safely be said that this is a consideration that will hereafter be fixed by the conditions to be met and not by any inherent limitation in our ability to produce units of any desired output. We now have units of 30,000 kw. capacity in service and still larger ones projected, and no limitations of design or material appear of such a nature as to place a stop to further progress along the same line.

At Omaha, in June 1898, the then president of our Institute, Dr. A. E. Kennelly, made an inaugural address upon the topic, "The Present Status of Electrical Engineering." This address constitutes a very convenient milestone by which to judge our progress since that time, and in this address I will take the liberty of quoting freely from this 1898 address of Past President Kennelly. In the matter of generator sizes, he says, "In 1884 a 50-kw. dynamo was considered a large machine, while a 100-kw. Edison steam dynamo was justly called a 'jumbo'. At present the largest size of generator built or building is of 4600-kw. capacity." In the 14 years from 1884 to 1898 the maximum size of generator therefore increased 46-fold, while in the 17 years since that time, the increase has only been a bout seven-fold. While the increase in capacity therefore has been a marked one, the rate of increase has not been so rapid during the last 17 years as it was in the previous 14 years, a result which naturally might have been anticipated. The future will undoubtedly continue to produce larger and larger capacity machines, the limit as to size being dictated by plant capacity and economic considerations and not by any inability to produce the larger sizes.

In the matter of selling price of such apparatus the following extract from Kennelly in 1898 may be of interest: "The price of dynamos in 1882 was about 20 cents per watt of output, while dynamos of similar running speed for comparatively small sizes without switchboards now cost about 2 cents per watt." The speed and size of these units is not mentioned, but it may be said in comparison that nowadays prices are frequently quoted below one-half cent per watt. In this respect again, the improvement in the last 17 years has not been so marked as it was in the 14 years previous, a result that is only to be expected. In the next succeeding period it is probable that a still smaller degree of improvement will occur. We are approaching a saturation point in this respect.

It may be well to point out some of the reasons for this approach to saturation in the matter of costs. The two fundamental costs of electrical apparatus are those of labor and material. In regard to the item of labor, I submit that it is safe to predict that the tendency for the future will be for the cost of labor to increase rather than decrease. Economies in the use of labor will undoubtedly take place by the introduction of the methods of scientific management, etc., but these need not be expected to be revolutionary in character so far as cost of apparatus is concerned. The tendency of the labor item will unquestionably be toward appreciation rather than depreciation.

In regard to the item of material, modern design has approached very close to the physical limits of available materials. Take, for instance, the property of permeability possessed by irons. With higher permeability, making available greater flux densities, the cost of electrical apparatus might be considerably reduced. That the future will bring some improvement in this respect is unquestionable; but it is further highly improbable that this improvement will be of such a revolutionary character as to cause any sweeping change in the cost of electrical apparatus.

The hysteresis and eddy current losses that take place in irons and steels that are subjected to varying magnetic fluxes constitute another of the limits encountered in the design of electrical machines. Marked progress has been made in this respect in recent years. Our modern transformer steels in the matters of losses and iron aging qualities show a vast improvement over those formerly available. Unfortunately, these improvements have so far been accompanied by a decrease in permeability which is highly objectionable, particularly in rotating machinery. Unquestionably, further improvements will be made in the magnetic qualities of our irons and steels, but these improvements will probably make no revolutionary change in the costs of electrical apparatus.

The conductivity of copper and other metals is another physical property that sets a limit to the output and cost of our electrical apparatus. Apparently we have reached a definite limit in this respect. The conductivity of the copper of commerce is within an extremely small percentage of that of pure copper and we cannot expect to obtain a higher conductivity in copper than that of purity. There remains, of course, the possibility of using some metal other than copper, but at this present time there is very little promise in that possibility. There is apparently no metal that even approaches the space and cost characteristic of copper that makes it so essential to the construction of electrical apparatus. Aluminum is a competitor only when the volume of the conductor is not an essential element in design, as a transmission line and the like.

One of the most pressing of our existing limitations to a reduction in cost of electrical apparatus is that fixed by temperature rise. The output of a piece of electrical apparatus increases with the temperature rise, and the temperature rise in turn is dictated by the point of balance between the rate at which heat is put in and that at which it is taken out of a machine. The rate at which heat is put in depends largely upon such physical characteristics as hysteresis and permeability of iron and conductivity of copper, which characteristics are already being crowded to the limit by our modern designs. The rate at which heat is dissipated depends upon the efficacy of the ventilation methods used, and in this particular there is a considerable opportunity for improvement. The methods and devices for taking heat out of machines are just as important, when considering temperature rise, as the prevention of heat from entering. While there is unquestionably room for considerable improvement in this particular, there is a question as to whether it will cause any material reduction in the cost of such apparatus. The additional cost of applying the more efficient methods of dissipating heat will go far toward nullifying their tendency toward a reduction of cost.

However, there is one line of development that does promise some reduction in cost, and that is the tendency toward higher operating temperatures. In the past, the maximum operating temperature has been fixed by the disintegrating point of fibrous insulation, and this point has placed a very definite and logical limit to temperature rises in such machines. However, when types of insulation are used which do not have this definite temperature of disintegration, this reason for such a temperature limit disappears. Just how far we can go in apparatus temperatures without exceeding the safe limits of these heat-resisting insulations is as yet problematical. However, a limit to an indefinite extension in this direction is set by the temperature coefficient of copper conductors, the property that causes the resistance to rise with increasing temperature, thereby causing still higher losses and in turn still higher temperatures. If we go high enough, we will reach a point of unstable equilibrium in this temperature rise curve, where the apparatus will literally and automatically "burn out." This point is, of course, far above anything that is projected at the present time, but while we are looking for limits, we might as well recognize that such a one exists.

In the matter of power production therefore, although we have steadily improved in the past, both as to costs and as to performance, and although we may expect to continue this steady improvement in the future, we must not expect that these improvements will be of the same revolutionary character as they have been in the past. We can see ahead of us a definite limit beyond which it will be impossible to improve the methods of power production now in use. I do not mean to say that there will be no new or revolutionary methods developed in the future, but so long as we continue to get our power from falling streams and burning coal, we need not expect to see the same radical improvements in the future as have distinguished the past. To illustrate my point more fully, let us consider the nature of a water power. Water is evaporated by the action of the sun and is carried miles above the earth into the clouds. Here it is precipitated in the form of rain or snow and falls on the earth. The streams carry this water back to the ocean and it is then ready to repeat the cycle. Our existing water powers utilize an almost infinitesimally small part of this water over an almost infinitesimally small part of the total height to which the sun carried it. Insofar as is concerned the water we use over the head through which we use it, we do fairly well, but the part of the sun's energy which we thereby realize is so infinitesimally small that it puts us to shame. Some Westinghouse or Edison of the future will show us how to use the sun's energy directly. The point I wish to make is that the revolutionary improvements in power production methods of the future must come in a fundamental change of method rather than in the continued improvement of existing methods.

So much, then, for the methods of producing power. In the matter of utilization of power a few comparisons with the past may not be amiss. As indicated early in this address, the modern motor has reached a stage, insofar as efficiency is concerned, such that little improvement may be expected. We are within a comparatively small percentage of perfection in this respect. The progress of the future will undoubtedly come from improvements in methods of application, and in this direction the field is inexhaustible. For instance, the problem of applying electrically the large amounts of power which are demanded by our modern railroad trains has not yet received a solution which is satisfactory to all concerned. That the problem will be solved there is no doubt in my mind, but just how, is a question that I do not propose to discuss in this address. However, this is only one of the many problems that confront the electrical engineer. The devising of methods for the application of electricity to our modern industries constitutes the occupation of no small part of our fraternity; as witness the many pages in our PROCEEDINGS that have been occupied during the past years by the activities of the Industrial Power Committee. It is along this line that we may expect much of what the future may have to offer us of a revolutionary character.

In the field of electric lighting there have been developments of importance. After the telegraph, in point of time, the electric light was the first practical application of electricity.

Most of our modern development in electrical engineering has taken its initiative from the supply of electric lighting to our communities. In this matter of electric lighting let me quote again from Kennelly's 1898 address: He says, "The price of a 16-candle power incandescent lamp 16 years ago was about $1.00. Now it is about 18 cents. The best lamps at that time, under laboratory conditions, gave about 0.28 mean horizontal normal British candle power per watt, and under commercial conditions about 0.20. The highest pressure for which they could then be obtained was about 110 volts. At the present time, lamps are obtainable giving normally 0.4 mean horizontal British candle power per watt, while under commercial conditions the average lamp normally develops about 0.25 candle per watt. They can also be obtained (at 0.25 candle per watt) for pressures up to 240 volts, and are frequently installed on 220-volt mains."

Kennelly therefore records an improvement in 16 years of about 50 per cent in cost of lamps to the consumer and about 50 per cent in efficiency. The introduction of the metal filament lamp has enabled us today to record a much greater rate of improvement in efficiency than Kennelly did. He reported an improvement of about 50 per cent in efficiency in the 16 years previous to 1898. In the 17 years since Kennelly wrote, we have improved our maximum efficiency about 1000 per cent, an advance which is truly marvelous. But here is a field where we have a long way to go yet without reaching a possible limit. It is true that the melting point of the now available materials seems to place the limit of lamp efficiency at a point not much higher than that which we have at present. However, when we come to compare the efficiencies of even our best lamps with that attained by the fire-fly it is evident that we still have a long way to go before we have reached perfection.

In the matter of power transmission, progress during the past few years has been remarkable. In 1898 the record reads:—"The electric transmission of the power of falling water is a branch of engineering that has come into service since 1884, and is making rapid strides, owing to the recent successful employment of high voltages and multiphase alternating currents. It has been estimated that about 150,000 kw. of this class of machinery is installed on the North American continent, commercially transmitting power to various distances up to 85 miles, at various pressures up to 40,000 volts." Since Kennelly wrote, 17 years ago, the maximum transmission voltages have gone up about 3¾ times; the maximum then was 40,000 and now is 150,000 volts. The maximum distance of transmission has gone up about 3⅓ times, 245 miles as against 85, and the installed capacity of water power plants on the North American continent about 9 times, 1,350,000 instead of 150,000 kw. Kennelly also mentions in his record that "insulation testing sets have been made for producing alternating pressures up to 160,000 volts effective." In this respect we can go at least 10 times better than he reported, 1,000,000 volts from transformers having been made available on more than one occasion, and in some cases the voltage available from transformers has been pushed even higher. This matter of power transmission is a branch of our industry wherein the progress of the last 17 years since Kennelly made his record has advanced with probably greater rapidity than in any other branch. I feel very sure that the president of our Institute who comes along 17 years hence and compares the then conditions with my record will not be able to claim any such advance as that we now may claim over 1898. This follows because we are approaching some fairly well defined limits in these matters. For instance, in the question of increasing transmission voltages we are close to the corona limit. The appearance of corona in the transmission line means the continual loss of power and therefore corona cannot be tolerated to any appreciable degree. There are, of course, methods of increasing the voltage range somewhat before corona is produced, such as increasing conductor diameter, but it can be readily seen that the limits of such remedies will be reached long before transmission voltages have increased by the same ratio as they have in the past 17 years.

Another limit that we are approaching in the matter of power transmission is the economic one. Transmitted power costs more than that generated at the point of delivery on account of the cost of and the losses in the transmission line. There obviously is a limit to the investment that can be made in transmission lines and still be able to supply power with the same economy as it can be generated upon the ground. This consideration, coupled with the rapid advance in methods of generating power from steam, has in my mind placed an economic limit to the transmission of water power so that we cannot expect any such advances in the future as the past 10 or 15 years have given us. That there will continue to be improvement and advance, no one can doubt, but its rate will certainly be diminished.

Transmission by high-voltage direct current has received some attention of recent years. While there is no question but that the problems of pure transmission are much simplified by the use of direct current, the accompanying problems of the generation and utilization are so much intensified that nothing is to be gained in this manner. I would predict no material advance for the future in direct-current transmission of power unless some means, as yet undeveloped, is found by which its generation and utilization are made easier and safer than is possible at present.

And so we might go on indefinitely and draw comparisons with past practises. Always we find progress, always also we find that the rate of progress is not so high now as it was in previous years. This is but the working out of a natural law. Electricity is no longer the infant that it was formerly pictured, and cannot be expected to continue the rate of growth of the infant. It is attaining the vigor and strength of manhood. It is contrary to natural law that either a child or an industry can have rapidity of growth and at the same time strength and stability of character. Unquestionably the rapidity of our development is not so great now as it was when Kennelly spoke in 1898, and in this respect we are but following a natural law. At the same time, our vocation is acquiring a stability and permanence that are absolutely incompatible with the rate of growth that characterized its earlier years.

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THE ELECTRIC STRENGTH OF AIR—VI

BY J. B. WHITEHEAD

ABSTRACT OF PAPER

(1) Some of the simpler fundamental experiments on the electrical conductivity of the air are described.

(2) The theory of ionization in gases is outlined in non-technical language.

(3) Townsend's proof that the law of corona-forming intensity $E = 32 + \frac{13.4}{\sqrt{d}}$ is in accord with the theory of ionization by collision, is explained.

THEORIES OF GASEOUS CONDUCTION AND OF CORONA FORMATION

AIR, under ordinary conditions an excellent insulator, has also the remarkable property of becoming under certain circumstances a very good conductor. It shares this property with most other gases. Air becomes a conductor when exposed to Röntgen rays, cathode rays, ultra-violet light, radioactive substances and other similar influences. In particular it acquires exceptional conductivity in the neighborhood of sparks, brush discharge and the high-voltage corona.

What is the nature of the structure of the air which permits this change of behavior? This is a pertinent question in these pages, since it is this change which places a serious limitation on the use of high voltages. The study of this question has engaged the attention of experimental physicists for many years. It has proved one of the most promising fields for the investigation of, perhaps, the most important of all problems of the physicists, namely, the ultimate nature of matter. Progress in this investigation has been particularly noteworthy within the last fifteen years. Even electrical engineers have contributed in some measure to the results which have been obtained. It is now possible to make a number of definite statements as to the structure of gases, and in particular, to that of air. It is the purpose of this paper to outline the experimental basis upon which the modern conception of the structure of the air rests, and several resulting theories of the nature of the high-voltage corona. Effort will be made throughout to keep the description free from technicalities and to avoid as far as possible the introduction of mathematical treatment.

It is with some hesitation that a paper of this character is offered to the Institute. Engineers for the most part have only a passing interest in questions of pure physics. The daily work of most engineers does not involve problems requiring such knowledge. The study of physics, unfortunately, is reduced to an exceedingly small minimum in most of our engineering schools. But in electrical engineering particularly, there seems to be a special reason why the ultimate nature of electrical phenomena should be studied and increasing attention be given to the results of the investigation. Many of the most useful electrical phenomena are not understood, cannot be explained in terms of simpler phenomena, and represent, in many instances, the empirical results of the first discovery. As a consequence of these facts there has fortunately within the past few years been a noticeable recognition of the need of a deeper study of electrical phenomena. Manufacturers have established research laboratories from which results of the highest importance have already been received. National testing and standardizing laboratories have rightly conceived it a proper function to devote more attention to research: Independent workers in increasing numbers are devoting their attention to problems which seem most likely to lead to results of practical value: And lastly may be mentioned an increasing demand that engineers, during their formal training, devote more time to the study of the physical sciences, this demand having been created by wide spread recognition that the deficiency in this respect is a serious limitation.

The writer has also been influenced, in a year of enforced cessation of the experimental work which has been the basis of the foregoing papers of this series, by a desire, to make use of the opportunity to coordinate, as far as possible, the results of all of the papers which have appeared before the Institute on the subject of the electric strength of air, with the theory which we are today asked by the physicists to accept.

The Kinetic Theory of Gases. One of the strongest evidences of the correctness of modern theories of the electric behavior of gases is found in their accord with the kinetic theory of gases. This theory had been established practically beyond attack before the study of the electric properties was begun.

It will be recalled that the kinetic theory assumes that in structure a gas consists ultimately of molecules, which are its smallest indivisible particles. These molecules are in a state of irregular motion or vibration. They collide with each other rebounding to further collisions without definite law. The pressure of a gas in a closed vessel is due to the impact and rebound of the molecules against its sides. The increase in temperature is an increase in the velocity, and hence kinetic energy, of the individual molecules. Compression and expansion of the gas are accompanied by a shorter or longer amplitude of vibration of the molecule between collisions.

The mathematical study of a system of elastic spheres in some such state of vibration as has been described, does not present particular difficulties. The method is based on the principle of averages; that is to say, it does not consider the motion of an individual particle or sphere, but the average motion and average length of path between collision resulting from some presupposed state as to the total amount of energy associated with the entire system of moving particles. Such study has led to many expressions which have been used as a basis for test of the theory. All of the elementary laws of the behavior of gases concerning changes of pressure, volume and temperature, are found to be in accord with the theory, and it may be stated that while this theory can never be subjected to the rigid proof of actual observation, yet nevertheless results of the theory are so universally in accord with known facts as to place the correctness of the theory beyond all question. While a number of instances of this agreement may be mentioned, attention need only be drawn to the fact that particular confirmation is found in the phenomena relating to the specific heat of gases, to the second law of thermodynamics and to the laws of Avogadro, Boyle, and to Van der Walls' extension of the latter.

Of particular interest in the present connection are the results of the kinetic theory which indicate the size, mass, and space separation of the molecules. Our ideas of the diameter of the molecule are derived in several ways; from Boyle's law, and from the coefficients of viscosity, heat conductivity, and diffusion; they all agree very closely. The diameter of the molecule so indicated is about 3×10^{-8} cm. Similarly, the number of molecules per cubic cm. of gas at 0 deg. cent. and 760 mm. pressure is 2.75×10^{-19} power. The velocity of the motion of a molecule between collisions is on the average, in the case of air, about

48,000 cm. per sec., that of the hydrogen molecule being 186,000 cm. per sec. The mass of the molecule of hydrogen, the lightest of the gases, is 46×10^{-25} gm. The mass of the molecule of other gases is correspondingly higher, that of oxygen, for example, being 736×10^{-25}. The mean free path, or average length of path of the molecule between collisions under standard conditions, is about 10^{-6} cm.

It will be recognized that this conception and these figures are beyond the grasp of our senses. To assist the imagination, Lord Kelvin has stated that if a drop of water were magnified to the size of the earth, its molecules would be about the size of cricket balls. Perhaps it should be stated that the kinetic theory gives no evidence that the actual shape of a molecule is that of a sphere. The figures for the diameter represent the diameter of the range of action of a molecule in its relation to other molecules.

Electrical Conductivity of Air. As already indicated, the results of the kinetic theory and the magnitudes of the quantities given have been used with great advantage by investigators of the electrical properties of gases. We now proceed to a description of some of the methods of investigation and their results.

Air in the free state has electrical conductivity. This conductivity, however, is so small that to observe it directly is extremely difficult. The methods which have been used involve the observation of the rate of leak of static electricity from a charged body by means of the gold-leaf electroscope. The results obtained indicate that in the open the current passing between two parallel plates 10 cm. apart and each 100 cm. square, assuming perfect insulation, would be of the order of magnitude 3×10^{-18} amperes. This current, moreover, is the maximum which may be obtained and does not increase with increase of voltage; also it diminishes greatly if the air is confined in a closed vessel.

The conductivity may be greatly increased by exposing the air to Röntgen rays, ultra-violet light, etc., but in these cases also the currents are very small, necessitating the use of sensitive instruments such as the quadrant electrometer. The conductivity so imparted disappears after the exciting cause is removed, although not immediately. It may be removed by straining the air through glass wool, by drawing it through small metal tubes, and by applying an electric field.

These facts suggest that the conductivity is due to something mixed with the gas which also has an electric charge, since it moves out under the action of the electric field. Since the conducting gas as a whole shows no charge, there must also be equal amounts of positive and negative charge. The conclusion is thus reached that the conductivity of the air is due to its having mixed with it electrified particles, some positive and others negative. These particles are called ions, and air or other gas in a conducting state is said to be ionized. This idea is evidently in accord with the kinetic theory of gases, and it is only necessary to add to that theory the assumption that under certain circumstances some of the molecules acquire electric charges, either positive or negative. Leaving aside for later discussion the question how the state of ionization is brought about, it is possible to test the assumption in a number of ways.

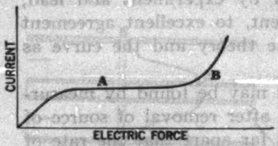

FIG. 1—CONDUCTIVITY OF AIR, SHOWING SATURATION CURRENT (A) AND BREAKDOWN (B)

With a constant exciting source of conductivity, as for example, a beam of Röntgen rays between two parallel plates forming the electrodes or terminals, we assume that a certain number of ions are formed each second. The volt-ampere characteristic of the air between the plates is as shown in Fig. 1. Under low values of electric intensity, the charged particles are carried to the plates with velocities at first proportional to the intensity. Thus the current is proportional to the voltage, or Ohm's law is obeyed. With increasing voltage the ions are swept out as fast as they are formed, but there can be no more current than there are ions, consequently the curve shows the horizontal portion known as the saturation current. With the further increase of voltage, the air breaks down in the form of corona or spark; we will return to this phase later. One of the interesting results of the theory as substantiated by observation, is the fact that with uniform ionization between the plates, and voltage high enough to produce saturation, the current increases with increasing distance between the plates. The greater the separation the more ions are formed, and, since all are swept out, the greater the current.

The ions which are formed by the ionizing agent, being charged molecules or particles, should disappear in three ways: (a) by recombination; (b) by diffusion to the walls of the containing vessel; (c) by being driven to the electrodes under the electric fields. Being in a state of vibration, positive and negative particles will sometimes collide and thus become neutral or no longer ions. Also some of them will drift to the sides of the vessel and will there be neutralized by the induced charges; that is, they give up their charges to the walls. Under the influence of an electric field they will be driven towards the respective electrodes, making collisions and some being neutralized, but finally disappearing as ions.

The current passing through a gas is evidently equal to the difference between the number of new ions formed per second and the number which disappear by recombination and diffusion. This relation can be written in simple mathematical form if the velocity of the ions under the electric force, and the coefficients of diffusion and recombination are known. These quantities have been found by experiment and lead, through the equation for the current, to excellent agreement between the equation based on the theory and the curve as observed experimentally.

The coefficients of recombination may be found by measuring the rate of decay of ionization after removal of source of ionization in air, between plates so far apart that the rate of recombination is far in excess of that of diffusion. Similarly by placing the plates very close together the rate of disappearance due to diffusion may be approximately measured being in these circumstances much greater than that due to recombination.

One of the most important properties of gaseous ions is their motion through the gas under the influence of an electric field. The velocity of this motion has been studied in several ways. One of the best known methods is to measure the electric force required to force the ions against a stream of gas moving with a known velocity. Suppose, in Fig. 2, that air is moving through the space between two concentric tubes with a velocity V, and that a beam of Röntgen rays passes through the tubes through small openings as indicated. The ions formed will move down the tube. If voltage is applied between the inner and outer tubes the ions will tend to move to the inner and outer cylinders. If the inner tube is divided at A, by moving it from right to left, along the axis, a point will be found where the right-hand section will just begin to receive a charge, as shown by the instrument E. This charge will be due to the ions which started near the point

B; all the other ions will be driven to the left-hand section of the inner cylinder. From the value of *V* and of the electric force, and the dimensions of the cylinders, it is possible to determine the velocities of the positive and negative ions.

Another method of measuring the velocity of the negative ions depends on the fact that negative ions escape from a zinc surface illuminated with ultra-violet light. The plan of the experiment is shown in Fig. 3. The zinc plate *A* forms one electrode, and a wire netting through which ultra-violet light may pass, the other. Alternating difference of potential is applied between *A* and *B*. A negative ion starting from *A* will move downward while the negative half-wave lasts, but will then start back to the plate *A* again. If, however, *B* is near enough, negative ions will reach it, and there will be a rate of leak from *A* which is observed at *E*. From the distance *A B*, the frequency, and the voltage, the velocity of the negative ions may be readily determined.

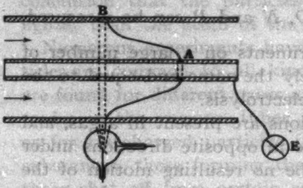

FIG. 2—MEASUREMENT OF VELOCITY OF IONS

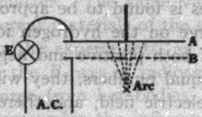

FIG. 3—MEASUREMENT OF VELOCITY OF IONS

From these and other experiments it is shown that the velocity of the positive ion in a field of one volt per cm. and in dry air at atmospheric pressure is 1.36 cm. per sec.; of the negative ion 1.87 cm. per sec.; in moist air the figures are 1.37 and 1.51. In oxygen the figures are about the same as in air; in carbon dioxide 0.76 and 0.81 and in hydrogen 6.7 and 7.9 cm. per sec. It will be observed therefore that in fields of high intensity, say 20,000 to 30,000 volts per cm., the ions may attain quite high velocities.

One of the most interesting conclusions reached through the assumption that gaseous conductivity is due to charged ions, is that the charge on an ion is the same for all gases, and that its value is the same as that carried by the atom of hydrogen in the electrolysis of solutions. This conclusion is reached by a consideration of the phenomenon of diffusion of gases, or the process by which two gases, if brought into contact, will slowly mix together. It will be seen that under the kinetic theory of gases this can only take place by motion of the molecules, and it is possible in this way to reach a conclusion as to how rapidly a molecule will move through a gas under the action of a force. In the case of diffusion, this force may be calculated on the kinetic theory from the pressure, temperature, and density of the gas. It is reasonable to suppose that if the molecule is charged, that is, if the gas is ionized under an electric force, the ions will move through the gas in much the same manner as the molecules do in diffusion. This idea leads to a simple relation between the coefficient of diffusion D, the charge on an ion e, the number of molecules N per cu. cm. of gas at pressure P, and the velocity of the ions U under unit electric field, viz.. $U/D = \frac{Ne}{P}$. As U, D, N and P can be measured, e may be found, and from experiments on a large number of gases is found to be approximately the same and equal to the charge on the hydrogen ion in electrolysis.

If both positive and negative ions are present in a gas, and in equal numbers, they will move in opposite directions under an electric field, and there will be no resulting motion of the gas. If, however ions of one sign or the other predominate, there will be resultant motion of the gas in the direction of motion of the excess ions. This motion has been frequently observed experimentally (discharge from points, corona, etc.), and a striking instance of it is described in the third of this series of papers.

The Electron. The first step towards the proof of the independent existence of ions may be said to be due to Crookes, who suggested that the cathode stream, or the bundle of rays which always appears to leave the surface of the negative electrode in a vacuum tube, was, in fact, a stream of distinct negatively electrified particles. The evidence of this was found in the shadows cast by the objects placed in the path of the rays, in heat generated at their point of impact, and in their deflection in a magnetic field. It had already been proved by Rowland that a moving electric charge is equivalent in magnetic effect to an electric current. The suggestion of Crookes was that the moving particles were charged molecules.

Following the idea of Crookes, J. J. Thomson in 1897 announced his remarkable experiments showing that the particles in the cathode stream are much smaller than molecules and that their mass is, in fact, only about 1/1800 that of the hydrogen atom in electrolysis, the lightest particle known up to that time. The experiments have been widely described and are well known. In the first of them, by making use of the amount of deflection of the rays in electric and magnetic fields of known intensity the ratio e/m of the charge to the mass of the particles was deduced and also the velocity with which they moved. In subsequent experiments by making use of the fact that, in the formation of water drops by condensation, the first drops form on the negative ions, the value of the charge on the ions was determined and was found to be equal to the charge carried by the hydrogen ion in the electrolysis of solutions. This value taken in conjunction with the ratio e/m leads to the conclusion that the particles in the cathode stream are far lighter than the atom of the lightest known substance.

Numerous experiments have shown that these smallest particles are common to all kinds of matter. The same values are found for different gases and different materials of the electrodes in the vacuum tubes used in the experiments, as well as for the charged particles forming the B-rays of radioactive substances, those forming the discharge from hot bodies, and those shot off from certain substances under the influence of ultra-violet light. The newly discovered particles were called by Thomson "corpuscles," but they are now more commonly known as "electrons." They carry invariably a negative electric charge of about 4.7×10^{-10} c.g.s. electrostatic units. So far as is known they have no existence independent of their charge and are in fact generally supposed to be the elementary electric charge. They move with different velocities according to the value of the electric force acting on them. Thomson's values in vacuum tubes were in the neighborhood of 2.6×10^9 cm. per sec., while those observed in the B-rays are even higher, approaching the velocity of light (3×10^{10} cm. per sec.) The independent existence of individual ions has been shown in a beautiful manner by Millikan and by Wilson. The former has been able to study the motions in an electric field of extremely minute oil drops, so minute that their rate of fall is very slow. The method involves the microscope and powerful illumination from the side. The oil drops pick up one or more ions and become charged particles. Their rate of fall or rise in the electric field between two parallel plates permits their charge to be calculated. It is found that the increase in charge as the drop picks up more ions, is always a multiple of the charge of the negative ion as found by other means, thus actually isolating the change in charge due to the accession of a single ion.

Wilson, making use of the powerful illumination of small water drops in much the same way, has been able to photograph the path of the positive ion or α particle from radium. Water drops, on the expansion of water vapor, form first around negative ions. If water vapor is subjected at the instant of expansion to the action of radium, the negative ions, formed by the collision of the α particles with the molecules of the water vapor, become centers of condensation, and so form tiny clouds in the general appearance of a thread, along the path of the α particles. If a photograph is taken at the instant of expansion, the paths of the α particles and also of the β particles or electrons are shown with remarkable clearness.

The electrons are supposed to be a common constituent of all matter, and now play a most important role in all modern physical theory. By assuming the presence of varying numbers and arrangements of them in the atoms, and that they are in motion, many phenomena, particularly those of light and radiation, may be explained. In this paper, however, we are only concerned with the part they play in the theory of the conduction of electricity through gases.

Conductivity Due to Electrons. In conductors the electrons are supposed to be very loosely bound to the molecules so that there are large numbers always free, and these conduct the current by motion under the electric force. In a gas, the molecules are in violent motion, and some of their collisions are violent enough to knock off an electron. This electron may attach itself to a neutral molecule forming a negative ion, or it may recombine with a molecule which has already lost an electron, forming again a neutral molecule. A molecule which has lost an electron becomes a positive ion. An ion, whether positive or negative, may attract to itself other neutral molecules, thus forming a charged aggregate of mass larger than the molecule. These aggregates are more commonly found in gases at high pressure, as for example in air at atmospheric pressure. While all these phenomena apparently are common to all gases, we will confine our discussion to the air.

In free air, then, there is always present, on the average, a certain number of free electrons and molecular ions, as the result of collisions and recombinations. It is these ions which impart to air its small conductivity at atmospheric pressure. The number of free ions at atmospheric pressure as deduced from this conductivity is about 1000 per cubic centimeter, whereas the number of molecules per cubic centimeter is 3.5×10^{19}; very few ions therefore are required to show conductivity. This inherent conductivity is so small, however, that it can be observed only with difficulty. Its small value may be appreciated by remembering that air is one of the best insulators known.

Beyond the saturation current of Fig. 1, further increase of voltage results in the break down of the air in the forms of luminous discharge such as the brush, the spark or corôna. The theory of ionization has been applied to this region of the curve for the case of parallel plates, and lately to the formation of corona on round wires. The spark and the arc have also been studied but without the striking confirmation found in the two cases mentioned. We will review briefly the case of the passage of current between two parallel plates, and from the information so gained consider the formation of the corôna.

THEORIES OF CORÔNA FORMATION

The sharp turn upwards of the curve of current between parallel plates in Fig. 1 with increasing voltage, marks the region at which sparks begin to pass. This curve may now be completely explained by calculation of the motion of the gaseous ions, if the assumption is made that an ion either positive or negative may in an electric field acquire sufficient velocity to cause, on collision with a molecule, its break-up into ions. This assumption, first suggested by J. J. Thomson, has been developed into an extensive theory by J. T. Townsend under the name "ionization by collision." This theory has been widely substantiated by experiment, and is now accepted as the basis upon which all phenomena of electric discharge or conductivity of gases must find their explanation.

While all phenomena of spark discharge are of first importance to the engineer, it is probable that no single one has attracted so much attention of late as the corona formed on round wires. While experimental determination of the voltage at which corona appears on clean wires may be made with a high degree of accuracy, including the effects of temperature, pressure, etc., and while the values of the losses between transmission wires due to corona under different conditions may be predicted quite closely, it remains a fact that none of the phenomena have been satisfactorily explained. The experiments in substantiation of the theory of ionization by collision, have been carried out at low pressures and with parallel plate electrodes, consequently the results have not been directly applicable to phenomena at atmospheric pressure and other forms of electrode.

Townsend has lately attempted to explain the law governing the appearance of corona on round wires. The explanation does not extend to the loss between wires, but it is important to all who are concerned with problems affected by the formation of corona. It is largely the hope of being able to present an outline of this explanation to electrical engineers that has led to the preparation of this paper. It will be necessary, for a proper understanding of the explanation of corona formation now offered, to review briefly two or three fundamental experiments.

We have already noted that the negative ion, or electron, is much smaller than the positive ion which is usually of the size of a molecule or larger. The electron moves faster in an electric field, and it generates ions by collision before the positive ion. This may be shown by taking the curve of Fig. 1 with concentric cylinders, first with the inner cylinder (or wire) positive and then negative. In the former case, the upward bend starts at much lower voltage, and therefore on the theory of collision, the negative ion becomes active before the positive.

We will describe two simple experiments as given by Townsend. Let ultra-violet light fall on the inner surface of one of two parallel plates; experiment shows that the plate will lose a negative charge. Let n_0 be the number of negative ions set free per second by the light. If the opposite plate is positively charged and if the potential gradient is low, no ions will be produced by collision, the n_0 ions will travel to the positive plate, and the current will be independent of the distance between the plates. If, however, the electric intensity is high enough the ions will produce others by collision. Let α be the number of new negative ions produced by a negative ion in going through one centimeter of gas, and n be the total number thus resulting in a layer of thickness, x, measured from the negative plate: then

$$dn = n\,\alpha\,dx$$

$$\log n = \alpha x + \text{const.}$$

$$n = n_0\,\epsilon^{\alpha x}$$

Since when $x = o$, $n = n_0$

Thus for distances l_1 l_2, etc.,

$$n_1 = n_0\,\epsilon^{l_1 \alpha},\ n_2 = n_0\,\epsilon^{l_2 \alpha}, \text{ etc.}$$

$$\therefore \frac{n_2}{n_1} = \frac{n_3}{n_2} \text{ etc.} = \epsilon^{\alpha\,(l_2 - l_1)}$$

The experimental proof consists in showing that the currents which are proportional to n_1, n_2, etc., increase with the distance between the plates in accordance with the exponential law indicated. Also in showing that for the same pressure and potential gradient α is constant for all distances.

Again, if n_0 ions are produced by Röntgen rays, in the air between two plates, a distance l apart, in a layer dx, at distance x from the positive plate, a number $\frac{n_0\,dx}{l}$ are generated by the rays. In passing through a distance x, acted on by the electric force X, these produce by collision $\frac{n_0\,dx}{l}\,\epsilon^{\alpha\,x}$; thus the number of negative ions reaching the positive plate is

$$n = \int_0^l \frac{n_0\,\epsilon^{\alpha\,x}\,dx}{l} = \frac{n_0\,(\epsilon^{\alpha\,l} - 1)}{\alpha\,l}$$

The ratio n/n_0 is given by the currents, n_0 being the value when no ions are produced by collisions, *i.e.* the saturation current, and n the value under the electric intensity X. The proof of this formula is found experimentally in the facts that n/n_0 varies with l as indicated, and that α is constant for different values of l.

From experiments of this nature it was found that with constant pressure and increasing electric force, X, α increases to a maximum value. This is in accord with the theory, since α must have a limiting value represented by the total number of collisions it makes with molecules in passing through one centimeter, each collision resulting in the forming of a new ion. Obviously α will also vary with the pressure, since, on the kinetic theory, the space separation of molecules increases with decreasing pressure. This is also proved by the experiments. With decreasing pressure and constant electric force, α first increases, since the velocities of the electrons first increase due to the longer time they are acted on between collisions by the electric force. With further decrease in pressure the velocities of the electrons continue to become higher, but the number of molecules per centimeter of path decreases and consequently α decreases again. These facts are stated more generally by Townsend as follows:

"In passing through a centimeter in a gas an ion traverses free paths of various lengths between the collisions. The chance of producing a new ion by collision will depend on the velocity at impact, and this is determined by the force X and the length of the path which is terminated by the collision. The lengths of the free paths are inversely proportional to the pressure, so that if the pressure is increased from p to zp all the free paths will be reduced to $1/z$ of their original value. If the force X remained unaltered, the velocities on collision would be reduced, but if the force is increased to zX the velocities will be restored to their original values and the number of ions arising from a given number of collisions will be the same as before. Since the total number of collisions per centimeter is increased in the same ratio as the pressure, the value of α will be increased to $z\,\alpha$, when X and p become zX and zp respectively Hence the three variables must be connected by an equation of the form

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right)\text{''}$$

The following figures in support of this reasoning are given by Townsend as being typical of a large number of observations:

$p = 2$ mm. $X = 262$ volts per cm. $\alpha = 3.7$
$p = 4$ " $X = 525$ " " " $\alpha = 7.4$
$p = 8$ " $X = 1050$ " " " $\alpha = 14.8$

The strongest substantiation, however, lies in the fact that if α be determined for various values of X and p, and if $\frac{\alpha}{p}$ and $\frac{X}{p}$ be used as coordinates, all the points will be found to lie on a smooth curve, thus giving the graphic form of the equation

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right)$$

This relation between α, X and p is the concrete expression of the fundamental assumptions of the theory of ionization by collision. It is the instrument which Townsend uses most freely, and an instance is shown in his explanation of the corona.

The values of α at low pressure (1 mm.) as taken from Townsend's results vary from 10 for $X = 1000$ volts per cm. to 0.7 at 100 volts per cm. One curve shows even lower values for α and X; at 1 mm. pressure and 60 volts per cm. α is 0.1. Thus we would deduce that at 760 mm. under a gradient of 45,000 volts per cm., 76 ions would be produced by one electron in moving through one centimeter. For smaller forces the value of α becomes rapidly smaller, and if we recall that the sparking gradient in air between parallel planes at 760 mm. pressure is about 30,000 volts per cm., the above figures indicate that sparking or other form of breakdown is caused by very few ionizing collisions. It should be noted, however, that all of these figures are taken from experiments at low pressure, 2 mm. to 8 mm., and the values of α are based on measurements of current at values of X/p, which would cause sparking at atmospheric pressure; consequently conclusions as to phenomena outside the range of observation should be taken with caution. At 30,000 volts per cm. and 760 mm. pressure X/p is 39, whereas Townsend's lowest values of X/p for air are between 50 and 60, and as stated, the observations were made at pressures far below 760 mm.

Spark Discharge. Most of the results we have mentioned were obtained under conditions in which negative ions alone are active. But the positive ions also may become ionizing agents. In generating ions by collision, the negative ion at each collision creates a negative and a positive ion. If in the experiment with parallel plates, the separation of the plates is increased, while X and p are kept constant, the current reaching the positive plate increases faster than is indicated by the expression $N_0 \epsilon^{a}$ which is based on the assumption that only negative ions generate new ions by collision. It may be shown that this increase can be explained on the assumption that positive ions also, if allowed a long enough path and subjected to a great enough force, will act as ionizing agents. By considering now two quantities α and β, the number of ions generated by the negative and positive ions respectively, in moving one centimeter, the value of the current may be readily calculated, and conclusions may be reached as to how α and β vary with the electric force and the pressure. The results are again in excellent agreement with the theory.

One of the most remarkable and accurate agreements is found in the matter of sparking potential. It will be readily seen that when both positive and negative ions are generating ions by collision, if the distance between the parallel plate electrodes is increased while the electric intensity between them remains constant, more and more ions will be formed and there will come a distance of separation at which the ions will become self-perpetuating or the current will continue indefinitely, independently of the original supply of ions due to ultra-violet light or Röntgen rays, etc. It is an important assumption of Townsend's theory that this condition is equivalent to the passage of a spark. As already stated, the values of the electric force and distance between parallel plates for this condition as indicated by the theory are in practically complete agreement with the long-established values of the sparking potentials between parallel plates.

Having given this brief description of Townsend's theory and experiments, we proceed to the explanations which have been offered of the formation of corona on round wires.

The Corona. That the surface electric intensity at which corona forms on round wires varies with the diameter of the wire, was clearly shown by Ryan in 1904. In 1911 Alexander Russell, using the accurate figures obtained by the author and given in the first paper of this series, showed that the law connecting the corona-forming surface intensity and diameter of wire, at constant temperature and pressure, may be expressed by the simple relation

$$E = 32 + \frac{13.4}{\sqrt{d}}$$

Shortly afterward Peek, exploring the influence of temperature and pressure, announced the following important modification of the above expression, in which δ is the "density factor" referred to 760 mm. and 25 deg. as unity.

(The writer's values of the constants have been retained).

$$E = \delta\left(32 + \frac{13.4}{\sqrt{\delta d}}\right).$$

The first attempt at an explanation of this comparatively simple expression appears to have been that of Russell. Noting that the corona sends out electromagnetic waves, Russell assumes that these waves are the cause of the ionization, and that they are set up by collisions between positive and negative ions resulting in neutral systems. The energy of the original separate charges is liberated as magnetic waves. We may with advantage quote him directly:

"Let us suppose that n is the concentration of the positive and negative ions in the corona. By the molecular theory of gases we know that the number of collisions per second between pairs of ions will equal αn^2, where α is a constant. The total number of collisions per second per unit length of the wire will be $2\pi a (\alpha n^2)$, and we may assume that violent ionization begins when this attains a certain constant value. Hence, so far as the size of the inner wire is concerned, the critical value of n varies inversely as $\sqrt{a}$. If we suppose that the value of the electric stress R at the surface of the corona is constant, and remember that the concentration n of the ions in the corona is proportional to the potential gradient across it, we get

$$R_{max} = R + \frac{B}{\sqrt{a}} \text{''}$$

It is evident that this point of view does not include the idea of ionization by collision. It appears to present several difficulties. For example, it does not suggest how the original supply of positive and negative ions is furnished, also it assumes that the kinetic theory of gases holds within the corona, and that the potential gradient throughout the corona is the same as at the surface of wire. The assumption that electromagnetic waves can cause ionization is of course justified, (Röntgen rays, etc.) but the other assumptions require proof. In spite of the attraction of the simple explanation of the inverse square root of the diameter, the explanation does not appear very satisfying.

Bergen Davis in his paper before the Institute entitled "Theory of Corona" frankly bases his theory on the ideas of Townsend and in fact starts from the expression $n = n_0 \epsilon^{\alpha x}$ which is explained earlier in this paper. It will be recalled that n_0 is assumed as the number of negative ions crossing unit area of a plane in a gas, and that under ionization by collision in which α is the number of new ions produced by one ion in moving through one centimer, n is the number of negative ions crossing unit area of a plane or reaching an electrode at distance x.

Davis's suggestion then is that under the alternating potential of a high-voltage wire, the negative ions, always present in the air, move inward on one half-wave and in so doing create new ions. On the next half-wave they move out, some recombining, but on the whole more remaining than on the foregoing half-wave. These in moving inward and thus reaching a more intense field, create more ions, the whole process being cumulative, until finally the number n reaching the conductor attains a critical value necessary for the appearance of the corona. In the development, the plane of n_0 is a cylinder around the wire, of such radius b that the electric intensity X_0, uniform over all this surface, has the value of the least potential gradient at which ionization by collision takes place. The radius b of the cylinder across which n_0 ions pass when corona forms, thus depends on the radius a of the wire, on the voltage E, and the distance R to the opposite conductor.

In the brief description of Townsend's theory above, the values of α were studied for uniform fields of force and α was found to be constant as long as the electric intensity and pressure were constant. Obviously the electric intensity is not constant in the neighborhood of a round wire, and it is a feature of Davis's discussion that he writes the above relation between n, n_0 and α in the form $\frac{n}{n_0} = \epsilon^{\int_a^b \alpha\, dx}$, noting that since α is a function of X it must be a function of x, the distance from the center of the wire. He then introduces an expression for α in terms of x as developed in an earlier paper of his own and supported by experiments by Bishop giving indications of the amount of energy required to ionize a molecule. A discussion of the form of the expression of α and its integration, and the subsequent handling of the equations, need not be attempted here, as the original papers may be consulted. It will suffice to state that after several radical assumptions Davis reaches expressions between radius of wire and critical intensity which agree closely with the experimental results of Peek and those of the writer.

The discussion contains so many assumptions which cannot be tested that it leaves the reader in considerable doubt as to its accuracy. Two conspicuous difficulties may be mentioned. First, no account is taken of the ionizing action of the positive ions, although it is practically certain that in all forms of spark discharge they play an important part. Second, the agreement between the theory and the results of experiment depends on the author's assumption that the minimum ionizing intensity for air at atmospheric pressure has the value 26,600 volts per cm. All observers now agree that the value of this intensity is between 30,000 and 32,000 volts per cm.

Townsend's Theory of Corona Formation. Until quite recently, practically all of the tests of the accuracy of the theory of ionization by collision have been based on experiments at low gas pressure. The greater part of the experimental work of Townsend and his co-workers has been done at pressures below 8 mm. of mercury. Owing to the longer free paths of the gas molecules at low pressures it is easier to trace the changes in conductivity due to the presence of ions, and consequently the law and resulting theory as to the nature of the phenomena are more readily studied and developed. It is for this reason that the theory of ionization by collision, as developed by Townsend, and as very briefly outlined above, does not lend itself readily to the explanation of arc, spark and other types of discharge at atmospheric pressure. Townsend has, however, applied the theory to the phenomena of spark discharge at low pressures and has shown a remarkable agreement between theory and experimental observation. In explaining the corona at atmospheric pressure he makes use of this agreement since he considers the corona a particular form of spark discharge.

In brief outline, Townsend's proof that the corona may be explained by the theory of ionization by collision consists in three steps:

(1) The laws of sparking at low pressures between parallel plates are in accord with the theory of ionization by collision;

(2) The fundamental relation of the theory, connecting pressure, electric force and the number of ions generated by a single ion in moving one centimeter $\left(\alpha = p f \left(\frac{X}{p}\right)\right)$, when applied to a concentric wire and outer cylinder, leads to a simple relation between radius of wire, electric force and pressure which is in agreement with the results of experiment.

(3) The values of electric force necessary to form corona are in agreement with the forces which may be calculated from the laws of sparking between plates.

(1) All three of these steps are necessary for complete identification of corona as a case of ionization by collision, but our

interest lies chiefly in the third. We will, however, first indicate briefly the agreement mentioned in the second step, omitting entirely discussion of the first, since the nature of the proof has already been suggested and further discussion would lead beyond the scope of this paper.

(2) The relation mentioned as the second step of the proof is that when corona is formed on wires of different radii at different pressures the product $a \times p$ is a function of $a \times X$ where p, a and X are pressure, radius, and critical surface intensity. In other words, if a and p are varied so that their product is constant then aX will also be constant. This relation follows simply by comparing the number of new ions generated by a single ion in moving through corresponding paths in two cases of concentric wire and cylinder, one in which the radii and pressure are a, A and p, and the other in which they are ka, kA and p/k. The proof need not be given here. Townsend quotes Watson's results as follows, in support of the correctness of this reasoning; the values of p and a were chosen so that the product ap has the same value.

p	a	X	ap	AX
760	0.1	75	76	7.5
560	0.136	55	76	7.5
360	0.211	34	76	7.2
760	0.2	61	152	12.2
560	0.272	44.5	152	12.5
360	0.422	28.5	152	12
760	0.5	46.5	380	23.2
560	0.68	35	380	23.7
360	1.055	22	380	23.2

It will be noticed that the product AX is constant for ap constant. In a recent paper Townsend and Edmunds have reported observations of the corona-forming intensity on five sizes of wire (0.006 to 0.476 cm.) in two sizes of cylinder (1.98 and 7.45 cm.) over a range of pressure one mm. to 760 mm. These results offer a much wider range for comparison than those of Watson. A large number of values of aX were obtained for each of 18 values of ap. The agreement in each case was very good.

(3) The simplicity of the form of the expression connecting critical corona intensity with the radius of the wire at atmospheric pressure has always suggested that it should have a

simple explanation. Townsend has been the first to offer the explanation. As often happens, it is simple enough to cause surprise that it has not been seen before. Further, it depends on the theory of ionization only insofar as does the phenomenon of spark discharge. Explain sparking on any other theory and the law of corona formation is explained on the same theory. It should be noted, however, that there are in reality no other theories of sparking which have been developed to an extent comparable to that of ionization by collision.

Assuming that the electric intensity or force at the outer boundary of the corona is 30 kilovolts per centimeter, the minimum sparking intensity for air, the average intensity in the corona is $\frac{X_1 + 30}{2}$ X_1, being the intensity at the surface of the wire, at which corona is formed. Thus on the assumption that corona is a form of spark discharge this average intensity should be equal to that required to cause a spark to pass between two parallel plates separated by a distance $S = c - a$, c being the radius of the outer boundary of the corona, and a that of the wire. Now the law for sparking potentials between plates separated by small distances has long been known and is $V = 30S + 1.35$, V being in kilovolts. Consequently by the above assumption

$$\frac{X_1 + 30}{2} = 30 + \frac{1.35}{c - a}$$

The radius of the corona c may be expressed in terms of X_1 by noting that forces at points outside the wire are inversely as their distances from the center. Thus X_1, being force at distance a, and 30 that at distance c, we have $c = \frac{a X_1}{30}$. Substituting:

$$\frac{X_1 + 30}{2} = 30 + \frac{1.35}{a \left\{ \frac{X_1}{30} - 1 \right\}}$$

or

$$X_1 = 30 + \frac{9}{\sqrt{a}}$$

which agrees very closely indeed with the author's results as given in the first and second papers of this series, and also with those of Peek and Watson

Although, as stated above, it is not necessary to invoke the theory of ionization to deduce the above relation at atmospheric pressure from the laws of sparking, the same cannot be said when the influence of pressure is to be included. The aid given us by the theory at this point is perhaps one of the most satisfying evidences of its correctness. We have already indicated that the theory shows that for the formation of corona Xa is a function of pa. Applying this to the above relation between a and X, and expressing p in atmospheres, we have:

$$X_1 a = f\,(pa)$$

at $p = 1$,
$$X_1 = 30 + \frac{9}{\sqrt{a}}$$

or,
$$X_1\, a = 30\, a + \frac{9\, a}{a}$$

$$\therefore X_1\, a = 30\, pa + \frac{9pa}{\sqrt{pa}}$$

or
$$X_1 = p\left(30 + \frac{9}{\sqrt{pa}}\right)$$

This relationship was first shown experimentally by Peek, who verified it over a wide range.

While the above satisfactory explanations of corona formation, and the experimental results confirming them, are all based on the assumption and use of continuous potentials, it has been noted several times that corona-forming intensities have practically the same values for both continuous and the maximum values of alternating voltages. Although the exact identity of the values needs further proof, it is certain that, at low frequencies at least, practically the same law as to corona formation is obeyed by both alternating and continuous voltages. It has already been shown in these papers that the frequency, up to values of 2500 cycles, has little effect. The results of Ryan, however, indicate a pronounced effect at extremely high frequencies.

While, therefore, we now have a very satisfactory explanation of the first appearance of corona, there still remains the greater problem of the power loss above the corona-forming point. The results of Mershon and Peek show, over a wide range, the values of the loss which may be expected on transmission lines in the open. Experiments are now needed on clean smooth wires, and a study of the results in the light of the theory of ionization by collision. When this is done and the results compared with the interesting empirical law proposed by Peek, the electric properties of the air at atmospheric pressure so far as they are of importance to engineers will be fairly well understood.

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J. B. Whitehead, TRANS. A. I. E. E., XXIX–XXXIII, 1910-1914.

DISCUSSION ON "THE ELECTRIC STRENGTH OF AIR—VI" (WHITEHEAD), DEER PARK, MD., JUNE 29, 1915.

Percy H. Thomas: May I ask a question? Suppose we cool a gas down to a very low temperature—presumably there are then no free electrons in the unelectrified air. If so, what is the net result?

John B. Whitehead: So far as I know, the cooling of a gas does not result in the absolute disappearance of the free electrons present. The conductivity represented by the electrons which are present in ordinary atmospheric conditions is so extremely small that it is very hard to measure. We can understand that, by remembering that air is one of the best insulators that we have, but there is nothing in the theory as to the existence of these electrons—it is really more than a theory, because the existence of independent electrons has been shown photographically—to indicate that they would disappear. Of course, on cooling a gas the velocity of the molecules in their vibration, and their energy, will be decreased; thus the likelihood of the liberation of electrons will be less and consequently the number of electrons should be less and less. Whether they would ever disappear, I cannot say.

Percy H. Thomas: I had in mind very low temperatures, 10 or 20 deg. above absolute zero. Presumably, if there are only quiescent molecules, the tendency to collision would be reduced enormously for these low temperatures. There would then be no exciting electron to be considered.

John B. Whitehead: Suppose you carry the gas down to actual liquidation, you still have a liquid, and I believe I am right in saying that in liquid there is always some dissociation, and dissociation simply means the presence of charged ions. If we consider the solids, and take the extreme case of the conductors, there is always present a large number of free electrons.

Percy H. Thomas: I speak of air, eliminating the question of liquids and solids. It would seem in the air, which does not liquefy until it gets almost down to zero, there is a case in which you would not have that dissociation of solid and liquids.

John B. Whitehead: I do not see why if we have electrons free in gases at ordinary temperatures, they should entirely disappear at lower temperatures.

F. W. Peek, Jr.: Dr. Whitehead has done well to bring a review of the several electron theories before engineers. The first time that such a review was made for the Institute was in January 1911 by Prof. Ryan.

There are a few facts I should like to point out concerning my own work. My investigation of corona was begun in the early part of 1910. The laws of corona were deduced from data during the same year. Mention was first made of this work in an A. I. E. E. discussion in New York, January, 1911; the complete work done in this period was not published until June, 1911.

The visual corona law which has stood the test of a number of investigations, has, from the start, been more than an empirical one. I wish to emphasize this point. I will compare my development with the recent Townsend development given in the paper. The reasoning given in the development of this law in my June 1911 paper* is as follows: the gradient or stress to rupture air in bulk in a uniform field should be constant for a given air density or molecular spacing. This value is termed g_0, and is 30 kv. per cm. Energy is necessary to rupture insulation. In a non-uniform field, as that around a wire, the breakdown strength of air is first reached at the conductor surface; at an infinitely small distance from the conductor surface the stress is still below the rupturing gradient. Hence, in order to supply the necessary finite rupturing energy the gradient at the conductor surface must be increased to some higher value, g_v, so that at a finite distance away the gradient g_0 is 30 kv. per cm. This means that a finite thickness of the insulation must be under a stress of at least 30 kv. per cm. The rupturing energy is in the zone between g_v and g_0. Since the field is radial the thickness of this zone must be a function of the conductor radius.

A study of the data showed that when breakdown occurred the stress was always 30 kv. per cm. at $0.301\sqrt{r}$ cm. from the wire surface for all sizes of wire; the gradient, g_v, at the surface was higher for small wires than large ones (r is the wire radius in cm.) This is shown graphically in Fig. 1 for a large and small wire.

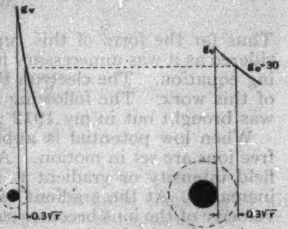

FIG. 1

The law may now be directly written from the above

$$g_v = 30\left(1 + \frac{0.301}{\sqrt{r}}\right)$$

For parallel planes or for air in bulk

$$r = \infty$$
$$g_v = g_0$$

Thus the strength of air is constant and equal to 30 kv. per cm., but in non-uniform fields it is apparently stronger for reasons explained above. If the air is made less dense, that is the molecular spacing is changed, the strength of air in a uniform field should decrease directly with the air density, δ.

$$g'_0 = \delta\, g_0.$$

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*TRANS. A. I. E. E., 1911, Vol. XXX, Part III, p. 1857.

However, for non-uniform fields, the energy distance should also change, thus,

$$0.301\sqrt{r}\,\phi\,\delta$$

This relation was predicted before tests were made. It was found from tests made in 1911 and published in June 1912, that the energy distance becomes

$$0.301\sqrt{\frac{r}{\delta}}$$

and the complete law

$$g_v = g_0\,\delta\left(1 + \frac{0.301}{\sqrt{r\,\delta}}\right)$$

Thus far the form of this rupturing energy has not been considered as it was unnecessary in order to develop a rational working equation. The electron theory is a useful instrument in all of this work. The following application of the electron theory was brought out in my 1912 paper.*

When low potential is applied between two conductors any free ions are set in motion. As the potential and, therefore, the field intensity or gradient is increased the velocity of the ions increases. At the gradient of $g_0 = 30$ kv. per cm. ($\delta = 1$) the velocity of the ions becomes sufficiently great over the mean free path to form other ions by collision. This gradient is constant and is called the dielectric strength of air. When ionic saturation is reached at any point the air becomes conducting and glows, or there is corona or spark.

Applying this to parallel wires: when a gradient, g_v, is reached at the wire surface any free ions are accelerated and produce other ions by collision with molecules which are in turn accelerated. The ionic density is thus gradually increased by successive collisions until at $0.301\sqrt{r}$ cm. from the wire surface where $g_0 = 30$ ionic saturation is reached or corona starts. *Air must thus be stressed over a minimum finite distance at a gradient of 30 kv. per cm. or above in order to bring any portion of it up to ionic saturation by successive collisions.* The distance $0.301\sqrt{r}$ cm. is, of course, many times greater than the mean free path of the ions and many collisions must take place in this distance. Thus, for the wire corona cannot form when the gradient of g_0 is reached at the surface, as at any distance from the surface the gradient is less than g_0 and a sufficient number of ions cannot be supplied to bring any finite thickness of the air up to ionic saturation.

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*F. W. Peek, Jr., Law of Corona II, III, Jan. 1912, 1913.

The gradient at the surface must, therefore, be increased to g_v, so that the gradient at finite distance away from the surface ($0.301\sqrt{r}$ cm.) is g_0. That is to say, energy is necessary to start corona. g_0, the strength of air, should vary with δ; g_v, however, cannot vary directly with δ because the greater mean path of the ions at low air densities, the greater energy distance is necessary. δ thus enters in the expression for the energy distance $0.301\sqrt{\frac{r}{\delta}}$. There can be no doubt that corona is spark from conductor to space.*

The corona sparking distance $c-a$ as discussed by Dr. Whitehead is

$$c - a = a\left\{\frac{X_1}{30} - 1\right\}$$

$$\text{Since } X_1 = 30 + \frac{9}{\sqrt{a}}$$

$$c - a = 0.3\sqrt{a}$$

as a is the radius.

$0.3\sqrt{a}$ is my "energy distance," or the finite thickness of air that must be broken down in the process of rupture,

$$0.3\sqrt{r}\text{ cm.},$$

as clearly brought out in my first paper.

This is also true for the further development of the formulas when

$$c - a = 0.3\sqrt{\frac{r}{\delta}}$$

which is also my energy distance or breakdown distance. Prof. Ryan in his 1911 paper also referred to a "striking distance."

This particular theory, discussed by Dr. Whitehead, assumes that the average gradient in a radial field produces the same effect as the gradient in a uniform field over the same distance; that corona is spark across distance $c - a$. On these assumptions it is shown that the corona law corresponds to an empirical spark-over law.

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*F. W. Peek, Jr., "Dielectric Phenomena in High-Voltage Engineering," Chap. IV.

I would like to call attention to the fact that for a wire in a cylinder, and ratio $\frac{R}{r} < \epsilon \overset{\sim}{<} 3$, corona and spark-over are simultaneous though the distance from cylinder to cylinder may be much greater than $c - a$.

Referring to loss measurements on polished wire which Dr. Whitehead suggests, such measurements have been made.* These measurements check the loss law.

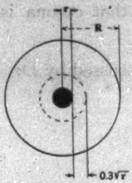

FIG. 2

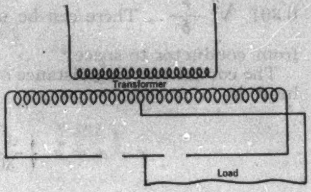

FIG. 3

I might state here that early in 1912 I rectified appreciable power at 200 kv. by corona. That it was possible to do this was brought out by a stroboscopic study that I made which showed that the positive corona extended out a considerable distance from a point, whereas the negative corona did not do so. By placing an electrode between two points, and connecting this electrode through the load to the neutral of the transformer, the mid electrode was always positive by contact with the corona stream, first from one needle and then the other, from half-cycle to half-cycle.† The diagram of connections, stroboscopic photograph, and oscillogram of rectified current are shown in Figs. 3, 4 and 5.

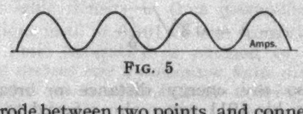

FIG. 5

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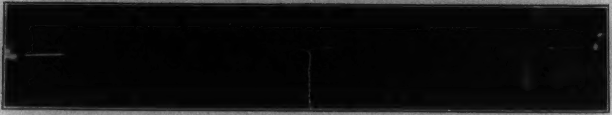
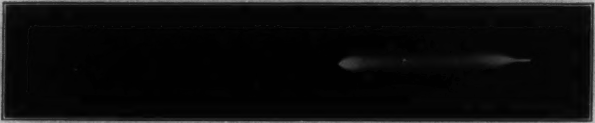
*F. W. Peek, Jr., "Dielectric Phenomena in High-Voltage Engineering."

†Dr. Steinmetz suggested the application of this principle to rectification.

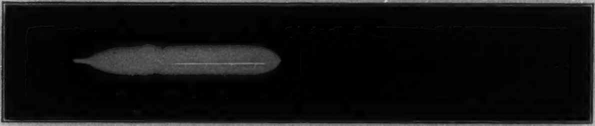


Electrodes [PEEK]

± Discharge without Stroboscope ± [PEEK]



− Discharge with Stroboscope + [PEEK]



+ Discharge with Stroboscope shifted 180 deg. − [PEEK]

FIG. 4—STROBOSCOPIC STUDY OF CORONA RECTIFIER

During the past two years I have investigated the corona due to transient voltages of extremely short duration. Visual corona may be produced by transient voltages whose duration is measured in micro-seconds. I hope, shortly, to publish these data.

E. E. F. Creighton: The subject as presented and discussed so far may seem to be very largely of a theoretical character, but in our lightning arrester work we find it of very considerable practical value. It is annoying to place a voltage on a lightning arrester, and have to wait for one of these little ions to come in the gap. That is what we have to do. They are apparently floating around wide apart, and if the impressed potential on the arrester is what is called the spark potential, it may be necessary to wait two or three seconds until a little ion comes in the proper position in the gap to start the discharge. I wonder if Dr. Whitehead could explain, from the work done and the theory given, the normal ionization of the atmosphere. Why do we always have about so many ions, never going much below a certain value? One would think that the electrons would combine in such a way that in some cases they would disappear entirely. It does not seem as though the collisions of the molecules would have enough energy normally to detach one of these electrons.

Harris J. Ryan: Dr. Whitehead's paper sets forth the electron theory and the theory of corona formation clearly in terms possessed by the electrical engineer. The atomic theory and the kinetic theory of gases have long been indispensable in the thermodynamics of working fluids. It now appears that the electron theory and the theory of ionization by collision will be equally indispensable in the electrodynamics of the electric fluid. The theory of ionization by collision is not a failure because it can account for little beyond corona formation. It is an infant theory, as yet, though growing rapidly. Even the mature kinetic theory of gases continues to grow. Many actions are inaugurated by corona formations. Some of them are mechanical, thermal, chemical, magnetic and those of the ultra-violet light. It is too much, therefore, to expect a theory of ionization by collision to account for the aggregate results of the complicated array of actions and inter actions that succeed corona formation.

In concluding his paper, Dr. Whitehead suggests the need of corona formation experiments on clean smooth wires and a study of the results in the light of the theory of ionization by collision. Thus the electrical properties of air at atmospheric pressure, so far as they are of importance to engineers, will be fairly well understood. In the limited sense intended, this is true. It is manifestly not intended to suggest that the end of corona studies as required for engineering is in sight. The power losses and injuries to insulators that may be caused by coronas, once they are formed, are highly dependent upon the time characteristics of the voltages with which they are produced. Besides, such effects are dependent in part upon the electric properties of the air, also upon its other physical and chemical properties, and for the rest upon factors that attend the particular circumstances.

Studies of effects following corona formation in relation to the time characteristics of the actuating voltage are now becoming important. The limited energy spark potential studies of Steinmetz and Hayden, the super-spark potential studies of Imlay and Thomas, and more recently of Creighton, and the line corona loss studies of Mershon, Peek and others have discovered and emphasized the importance of this field of investigation. Recent experiments have demonstrated that the high-frequency sine wave voltages sustained at 90,000 will discharge 15 in. from a blunt point to a grounded plate at one-third of the value of the 60-cycle voltage required to produce the same discharge. For an increase of one inch in the 15-in. gap the required increase in the 60-cycle discharge voltage was five times as much as the corresponding increase in the sustained 90,000-cycle voltage. The sustained high frequency coronas have many of the properties of the corresponding 60-cycle coronas, greatly exaggerated. They may speedily damage the most refractory insulations, even when present to a comparatively small extent. It seems likely that many forms of high-voltage transients may produce much the same phenomena, though with lessened intensity.

Every available form of voltage should, therefore, be used for experiment in this field. Such forms should include continuous voltages, sustained alternating voltages at helpful frequency intervals from low to high, single sudden impulses, single impulsing damped oscillations, intermittent wave trains of damped oscillations, and combinations of these with and without energy supply. Much attention has already been given to corona formation and effect under conditions that correspond more or less to those of standard operation. Air and other insulators must not fail unnecessarily under conditions brought about by accident or special practise. In many circumstances, accidents will produce almost every possible voltage-time variation, briefly sustained or as a transient. It would seem, therefore, that studies of the above sort, along with those suggested by the author, made with the guidance of the electron theory of ion formation and action, will lead to many useful results and the further growth of such theory.

Percy H. Thomas: May I ask Prof. Ryan a question? Assuming we have air stressed at 90,000 cycles continuous voltage below the corona point in a fairly uniform field, is there any noticeable rise in temperature in the air in a few seconds?

Harris J. Ryan: Not at all in the experiments we have performed. We have not undertaken any delicate means of detecting hysteresis in the air; that is, any heating due to the movement of the thousands of electrons present per cu. cm. They are being moved back and forth, and there must be some heat produced by them, but it is so small that in working around a good sized electrode, carrying high voltages, at high frequency, such heating was very slight. We have not been able to detect heating through the senses in the ordinary fashion and it would doubtless require very delicate means of determination.

Percy H. Thomas: That does not explain, then, the higher discharging power of the higher frequency voltage?

Harris J. Ryan: No.

Percy H. Thomas: Have you any explanation for it? It is most startling in the experiments you have made.

Harris J. Ryan: I took cyclograms of the energy that is consumed in the flames of high-frequency coronas, and the form of the cyclogram indicates that the ionization is continued from crest to crest of the voltage waves and that it does not go out in the manner that Dr. Whitehead has so beautifully shown when you use 60 cycles per second. He has shown that it goes out within 0.0001 of a second. When one is using 90,000 to 250,000 cycles per second, the crests of the waves return in less time than that required to extinguish the corona. The cyclograms determined that the high-frequency corona was acting very much as a non-changing resistance.

Percy H. Thomas: The fact that the loss in the corona varies as the frequency, suggests the loss of energy and heat as one of the explanations.

Harris J. Ryan: At these high frequencies, the power factor of the charging current issuing from a conductor in corona was found to be about *one quarter* of the corresponding power factor found at 60 cycles. The heating does not, therefore, continue to increase as rapidly as the frequency, though doubtless at 90,000 cycles the heating in the corona may be 400 times as great as at 60 cycles.

L. W. Chubb: The empirical formulas in the paper use the constants 30 and 32 for the ultimate strength of air. I would like to ask Dr. Whitehead if the breakdown for small distances between parallel plates is not larger than this.

J. B. Whitehead: Yes.

L. W. Chubb: When the distance between electrodes is too short for the ions to attain sufficient kinetic energy to produce new ions by collision we assume that the potential gradient can be raised to a value which will ionize the air by disruption of the molecule. This constant, which is apparently around 50 kv. per cm., would seem to have a place in the formulas for sparking and corona formation.

I believe that the range of application of empirical formulas should be stated by giving some kind of maximum and minimum limits for the variables involved. Such formulas derived from experimental results through a certain range are often misused because they do not show the facts in extreme cases.

John B. Whitehead: Only one or two of the points raised require answer. Before answering them I wish to say that perhaps the greatest value of the theory of ionization is that it allows us to base our explanation of all of these phenomena on the simple laws of mechanics. The only mysterious thing which we invoke is the presence of an electric charge and the presence of electric force, and if we accept these, and we must accept them, as they are observed facts, we can explain all gaseous conductivity in terms of the simple laws of kinetics and mechanics. That is the ultimate aim of all physics today, not only in the domain of electricity and magnetism, but in all other fields.

I think Mr. Peek and Prof. Ryan have both mentioned the importance of the time element in phenomena of this character, and there are already ample indications that in carrying the formation of corona down to an exceedingly small interval of time we have new factors appearing, Prof. Ryan has already published some of his results, and I hope there are others to come. I am glad to know that a further paper from Mr. Peek will appear shortly.

Mr. Creighton has asked the variation of the normal ionization of the atmosphere. The range of variation over the whole surface of the earth is about as 1 to 4, that is to say, the number of free ions as indicated by measurements on the conductivity, varies within about these limits. Now, the collision of molecules is not the only source of free ionization. Ultra-violet light, radioactive substances, X-rays, etc., or electromagnetic impulses of any character, may increase the ionization, and in consequence the conductivity of air. I do not think that physicists are ready to give a complete explanation of the free ionization of the atmosphere. Certain it is that part of it is due to collisions between molecules, but it is also recognized that the earth contains radioactive substances, which give off emanations and radiations. These vary in different locations, thus causing a variation in the normal state of ionization.

Mr. Chubb's question was as to whether in exceedingly small air gaps the strength of air is any greater than 30,000 to 32,000 volts per cm. It is, but only so in the case of air gaps which are so short that they are shorter than the mean free path of the molecules of the gas. These distances are so small that the experiments can be carried out only with great difficulty. Such phenomena are entirely outside of the relations we are considering in the present paper.

Presented at the 32d Annual Convention of
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Deer Park, Md., June 29, 1915.

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THE RELUCTANCE OF SOME IRREGULAR MAGNETIC FIELDS

BY JOHN F. H. DOUGLAS

Abstract of Paper

The development of the idea of magnetic reluctance is sketched, and the mathematical and experimental methods of determining it are first discussed. On the theoretical side it is the theory of complex quantities which leads to numerical results.

The electric field of an electric generator is next analyzed and made to depend approximately upon the reluctance of two-dimensional magnetic fields. This study indicates as preferable the one shown in Fig. 6 at the left.

The reluctance of these various magnetic fields is determined by experiments made on sheets of high-resistance metal cut in suitable forms, and by mathematical computation. These results are put into charts and formulas convenient for the use of those interested in electrical design. The results of the tests are proved to be more accurate than most of those already published. In particular, present leakage flux calculations are most in error.

Of more general interest are the plates of the shape of the magnetic lines of force in the various parts of electrical machinery. In particular, Figs. 42 to 48 include some new results. The flux lines in the corners of transformers and induction motors are there shown, and the exact solution to the much-discussed sine-wave alternator problem is there given.

The paper is divided into (I) Introduction, (II) Historical Development, (III) Description of Experiments, (IV) Accuracy of Results, (V) Conclusions. There are two appendices giving some mathematical details, for reference purposes.

I. Introduction

IF WE apply a difference of magnetic potential between two portions of the surface bounding a region of space, a certain amount of magnetic induction will be developed. If no induction crosses the remainder of the surface, we have a region which is a tube of induction, carrying a definite amo
of flux and consuming a definite amount of magnetic p
or mangetomotive force. All such magnetic fie
definite amount of reluctance, R, which i
applied magnetomotive force, M, to th
R =

ely
growth.
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magnetic circuit, were all
of Ohm's law for the magnetic

If there is no magnetic saturation present this reluctance is a constant. Only fields in media without saturation are considered in the following paper quantitatively. A few flux distributions in iron are, however, considered qualitatively.

The reciprocal of reluctance is called permeance or magnetic conductance. It is denoted by P; thus,

$$P = 1/R = \phi/M \tag{2}$$

If the lines of flux flow are everywhere parallel and the equipotential sections are everywhere the same, the magnetic field can be said to be regular. Such a field has a reluctance which can be readily expressed in terms of its dimensions. Thus,

$$R = L/\mu A \tag{3}$$

where L is the length of the magnetic flux path, A the area of its cross-section, and μ the permeability of the medium.

The above equation can not be used for an irregular magnetic field, except for an infinitesimal portion of a tube of induction, where infinitesimal values of L and A may be taken. Recourse must be had, therefore, to the fundamental definition of reluctance in equation (**1**) by considering the mutual relations between M and ϕ.

In this paper attention will be limited to some irregular two-dimensional magnetic fields; that is, to fields in which the flux lines are all parallel to some plane surface. The results, however, will be extended to apply to certain three-dimensional fields, by making approximate assumptions.

Owing to the fact that there is no magnetic insulator known, the magnetic fields around dynamoelectric machinery are very irregular. There is fringing of flux in the air gap, and leakage flux between the poles and around the slots. As a consequence designers have to use various correction factors, which even yet are more or less empirical. A study of the field of typical electrical machines was made in search of forms of magnetic circuit which needed study. In addition, on the mathematical
various cases were canvassed systematically. Beginning
simple shapes which led to simple integrals, study
ll possible forms up to those which involved in-
lt than the elliptic integrals of the first and
cases those promising any use were
he hope that some of the cases
be of use, that the experi-

ments and the mathematical work were carried out. Some of the results may be of use in analogous electrical problems.

The exact significance of equation (**1**) can best be obtained by reviewing briefly the historical development of the subject, tracing out the gradual unfolding of the conceptions involved. This will form the first natural division of the subject.

The various experimental methods which have been used will be described and discussed in the next section of the paper. Before describing a set of experiments made with high-resistance metal strips, an analysis of the magnetic field surrounding an electrical machine will be made.

The simplifying assumptions made in picking out certain two-dimensional fields as applying to what is in reality a three-dimensional problem are sufficiently serious to warrant discussion. Before passing on, therefore, to the conclusions, the accuracy of the results will be compared with that of the present methods.

The detailed mathematical treatment of the problem of the reluctance of irregular magnetic fields, is not included in this paper, because of its complexity and too special interest. Nevertheless the writer went over the ground, both mathematically, and experimentally, and found both methods needful for securing the best results. Those interested in this side of the subject, can consult the references given in the historical section of this paper. Those who prefer to use an analytical formula to a curve of permeance, can consult an appendix to this paper where the mathematical results are given. Another reason for their inclusion is that, while the figures were drawn carefully, greater accuracy might in some cases be desirable.

II. HISTORICAL DEVELOPMENT

Equation (**1**) is sometimes called Ohm's law for the magnetic circuit, from its similarity to the law of the same name in the electric circuit. This similarity is made the basis of the experiments described in this paper. Although simple in its final formulation, the law was discovered at a comparatively late date, because the ideas implied were of gradual growth. The existence of a potential function, the solenoidal character of magnetic force, the identity between electromagnetism and permanent magnetism, the existence of magnetic induction within iron, the idea of a closed magnetic circuit, were all needed for the final formulation of Ohm's law for the magnetic circuit.

The existence of potential as a function whose space derivatives give the components of the fields of force, is due to La Place[1], who used it with reference to the attraction of gravitation. The name itself is due to Green[2], who proposed it in his prize essay published in 1828. La Place showed that gravitational potential satisfies the equation

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} + \frac{d^2V}{dz^2} = 0 \qquad (4)$$

which is known by his name. This equation followed from the law of the inverse square of the distance discovered by Newton.[3] The suitability of such a function in the case of magnetism must have been apparent, because magnetic attraction was already recognized as a case of central forces. In 1785 Coulomb[4] demonstrated that the inverse square law was true for magnetism. The application of potential to magnetic theory followed at once.

In 1813 Poisson[5] called attention to a limitation to La Place's equation showing that it did not apply to the interior of the attracting body. In 1827 he derived the correct equation for the space within an attracting mass.[6] Owing to this difference, for a time the magnetic field inside a magnet was thought of as entirely different from that outside of the same.

In July 1820 Oersted[7] discovered electromagnetism, and a very short time after that Ampere[8] showed the equivalence of an electric circuit with a magnetic shell. Thus, the existence of a magnetic potential was proved for all points of the magnetic field except those within the magnetizing coil. The variation of magnetic potential within the substance of iron, however, was still unknown. These same experiments of Ampere's furnished us also with the idea of magnetic potential as related to an electric current. The unit of magnetic potential, however, came later.

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[1] Memoires de l'Academie Royal de Paris, 1782. Mechanique Celeste, Book 3, Chap. 2.

[2] Collected Papers p. 25.

[3] Principia, (1687) Book 3, Prop. 1-7. See also Thomson and Tait, "Natural Philosophy" Part 2, p. 9.

[4] Memoires de l'Academie Royal de Paris; 1785 p. 583; 1788, pp. 587 and 603.

[5] Nouveau Bul. Soc. Philomatique Vol. 3, pp. 388-392.

[6] Memoires de l'Academie de Paris Vol. 6, July 10, 1827.

[7] Schweigger's Journal Vol. 29, p. 273.

[8] Ann. de Chemie et Physik. 1820. Gilbert's Annalen, Vol. 67, (1821).

The concept of electric current as the universal cause of magnetism, even in permanent magnets was the last step in the development of the theory of magnetic potential.[9] In magnets revolving electrons within the atom constitute the source of magnetic potential.

The idea of a magnetic flux is also of gradual growth. At first, magnetic effects were considered as being exerted at a distance and manifested only when iron filings, a compass needle, or other magnetic body was present. However, the labors of Gauss and Weber, with their charts of magnetic fields, served to make the idea of fields of force more tangible. In 1813 Gauss[10] proved that the surface integral of magnetic force over any closed surface is proportional to the amount of attracting matter within it. This he proved directly from the law of inverse squares. The constancy of this integral could not help but suggest the idea of a flux or flow of force, constant in amount, from one magnet pole to another. This so-called solenoidal character of magnetic flux was, however, really implied in La Place's equation.

If H_x, H_y, and H_z are the three components of the magnetic field parallel to the three co-ordinate axes, and if the field is solenoidal,

$$\frac{dH_x}{dx} + \frac{dH_y}{dy} + \frac{d\,H_z}{dz} = 0 \qquad (5)$$

That electromagnetism was solenoidal followed at once from Ampere's discovery that a current was equivalent to a magnetic shell.

In 1831 when Faraday[11] discovered magnetic induction, he was inevitably led by the idea of cutting lines of force to the conception of the physical reality to be ascribed to them. His experiments in 1851[12] confirmed the solenoidal character of magnetism within the substance of the magnet itself. The concept of tubes of force and of induction followed at once.

The belief in a magnetic circuit of flux was of gradual acceptance. At first the identity of the tubes of induction outside the magnet with those inside was not clear. The term "magnetic circuit" was first used in 1833 by Ritchie,[13] and the term "closed magnetic circuit" in 1853 by Dub[14] and De la Rive.[15] The connection between magnetic force and induction in iron and the distinction between them, outside magnetic substances, was all that was then needed before Ohm's law for the magnetic circuit could be formulated. These were supplied by the discoverer.

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[9] Werner v. Siemens, Wiedeman's Annalen, Vol. 24 (1885), p. 94; Larmor, "Aether and Matter," (1904), p. 108.

[10] Werke, Band 5, p. 9.

[11] Experimental Researches, First Series, Vol. 1.

[12] *Ibid*, Vol. 3, Sects. 3077 and 3109.

The earlier theory of induction in iron took into account two distinct actions going on at once. First, there was a magnetic field inside the iron but due to outside influences. Second, there was a field due to the polarization of the iron itself. Although this conception is helpful, it delayed the formulation of Ohm's law for the magnetic circuit. It was on the basis of this theory that the early determinations of the quality of iron was made. In 1854 Kirchhoff[16] calculated the susceptibility of iron from some of Weber's experiments with an iron ellipsoid. In January 1873 Stoletow[17] first used the ring method of testing for determining the quality of iron.

We owe the statement of Ohm's law for the magnetic circuit to Rowland,[18] who not only determined the experimental relation between magnetic force and induction within iron, but also distinguished between the two. He originated the conception of magnetic force as a localized magnetomotive force. That is, magnetic field intensity was the gradient of magnetomotive force, rather than the flux density which would be set up in air, were the magnetic substance removed. The name of permeability as the ratio of magnetic induction developed in iron to that produced in other bodies is due to Lord Kelvin,[19] who attributed the idea of magnetic conductivity to Faraday. However, this point of view can be traced back as far as 1821, when Cumming[20] measured crudely what corresponded to magnetic conductivity rather than susceptibility. This was a rather close approach to the idea underlying Ohm's law for the magnetic circuit. Permeability as the permeance of a unit cube is of course due to Rowland.

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[13] *Phil. Mag.* Series 3, Vol. 3, p. 122.
[14] Poggendorf's Annalen, Vol. 90, p. 436.
[15] Treatise on Electricity, Walker's translation, Vol. 1, p. 293.
[16] Crelle's Journal, Vol. 48, p. 374.
[17] *Phil. Mag.*, Series 4, Vol. 45, p. 40.
[18] *Phil. Mag.*, Series 4, Vol. 46, p. 140, (Aug. 1873).
[19] Papers on Electricity and Magnetism, p. 484, (1872).
[20] Camb. Phil. Trans., Apr. 2, 1821.

Rowland also proposed, in his article, the ampere-turn as the unit of magnetic potential difference. In opposition to this Bosanquet[21] later proposed as a unit $(10/4\pi)$ of an ampere-turn. He also coined the term "magnetomotive force." This unit of Bosanquet's has persisted in spite of the priority of Rowland, and in spite of the return to the confusion between field intensity in air and induction in air, apparently because of the great influence of Maxwell. Maxwell[22] spoke of the intensity of a magnetic field as defined by the result of excavating a cavity in the iron of a particular shape. This "mouse and cheese" theory has always been a hindrance to electrical engineers, and manufacturing companies have always used magnetization curves in the form developed by Rowland.[23] Recent textbooks[24] still disagree as to the issue thus raised.

The term reluctance for magnetic resistance is due to Heaviside,[25] while the term permeance is due to S. P. Thompson.[26] The use of reluctance and Ohm's law for the magnetic circuit of dynamos was first brought to the attention of engineers by Hopkinson,[27] who however introduced a modification by using curves of induction plotted against field intensity, or *B-H* curves. The suitability of Ohm's law for parallel as well as series magnetic circuits was pointed out first by Kapp.[28]

The beginning of the theory of the reluctance of two-dimensional magnetic fields, was in the mathematical theory of goedetic lines of various kinds. This was next applied to the flow of electric currents in two dimensions and finally extended to magnetic problems. Maxwell attributes the application to the electric current to Prof. W. R. Smith,[29] and develops it himself in Chap. XII of his "Treatise." The following points are worthy of notice. (1) His treatment involves the theory of the conjugate functions of a complex variable. (2) Although this is the usual basis for the theory, his conclusions are independent of this method of treatment. (3) Part of this theory is essential to an understanding of the graphical and the experimental methods. (4) His exposition is confusing to those who do not care to go into the mathematical method deeply. (5) A brief outline of this theory is necessary.

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[21] *Phil. Mag.*, Series 5, Vol. 15, p. 205, (Mar. 1883).

[22] Electricity and Magnetism, Vol. 2, Sect. 398, p. 24, 3rd Ed.

[23] Ayrton and Perry, Jour. Soc. Teleg. Eng. & Elec., 1886, p. 518.

[24] Karapetoff, "Magnetic Circuit," 1st Ed. p. 12 and p. 266. Pender, "Principles of Electrical Engineering," Chap. II.

[25] *Electrician*, (London), Vol. 21, (1888), p. 27.

[26] Dynamo Electric Machinery, 4th Ed. (1892), p. 186.

[27] Phil. Trans. Royal Soc., 1886 Part 1, p. 331.

[28] Jour. Soc. Teleg. Eng. & Electr., 1886, p. 530.

[29] Proc. R. S. Edin., 1869-70, p. 79. See also Treatise on Electricity and Magnetism, 3rd Ed., p. 185.

The reluctance of an irregular two-dimensional magnetic field, such as *OAPB* in Fig. 1, is

$$R = R'\nu/t \tag{6}$$

where ν is the reluctivity or reciprocal of the permeability μ, t is the thickness, and R' is a constant which depends only upon the shape of the field. If we always work with a thickness

$$t = \nu \tag{7}$$

of the field, we see that R' is the reluctance of such a slice and is independent of the material. R' may be called the geometric reluctance of the field.[30]

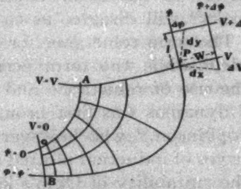

FIG. 1

Each line of flux may be characterized by a number called the flux function. This is defined as the amount of flux passing between this line of flux and an arbitrary point or zero of reference, and within a thickness of the field equal to its reluctivity. The flux function at a point is that belonging to the flux line passing through that point.

The geometric reluctance R' is expressible through the flux and potential functions. Thus in Fig. 1, the geometric reluctance of *OAPB* is

$$R'_{OAPB} = (V_p - V_o)/(\phi_p - \phi_o) \tag{8}$$

The total reluctance of a slice of any thickness can be obtained by combining equations (6) and (8). A study of the reluctance of two-dimensional irregular magnetic fields is nothing else than the study of the graphical and analytical relations between the potential and the flux functions.

Let us consider the field in Fig. 1 as divided by lines of force at equal increments of the flux function $\triangle\phi$, and also by equipotential lines at equal intervals $\triangle V$ which are equal to $\triangle \phi$. Let us consider that the field is divided also by parallel planes into laminae of a thickness $t = \nu$. The field is divided thus into cells each of which has a reluctance of unity, and all the angles of which are right angles. Moreover if the intervals $\triangle \phi$ and $\triangle V$ are sufficiently small, the curvature of the sides of the cells can be neglected. That each cell is a square, is easily seen from equation (**3**). Putting $A = t \times w$, the thickness being t and the width of the cell being w, we get,

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[30] Karapetoff, "Magnetic Circuit," Chap. 5, p. 93.

$$R = \frac{(\nu)\ (l)}{(t)\ (w)} = 1.$$

Since t is equal to ν, the length of any cell l must be equal to its width w. The dimensions l and w are, however, shown in only one of the squares of Fig. 1. The fact that the flux and potential lines form what may be termed curvilinear squares, is made the basis of the graphical method of determining the reluctance of an irregular magnetic field.

If we consider in Fig. 1 an infinitesimal square formed by two lines of flux, ϕ and $\phi + \triangle \phi$, and by the two equipotential lines V and $V + \triangle V$, we can see from the geometry of the figure that,

$$\frac{dV}{dy} = \frac{d\phi}{dx}; \qquad -\frac{dV}{dx} = \frac{d\phi}{dy} \tag{9}$$

Functions satisfying these relations are called conjugate functions. By differentiating the first of the preceding equations with regard to x and the second with regard to y, we obtain, after combining,

$$\frac{d^2\phi}{dx^2} + \frac{d^2\phi}{dy^2} = 0 \tag{10}$$

in other words the flux function, as well as the potential function, satisfies La Place's equation in a two-dimensional magnetic field.

The mathematical similarity between the flux and potential functions, suggests the possibility of transposing the roles of the potential and flux functions. It must be plain that, since the flux and potential lines form squares rather than rectangles, there can be no reason why one set of mutually orthogonal lines need be chosen as flux lines rather than the other. Thus for every two-dimensional magnetic field, there is an exactly similar field in which the roles of the two sets of lines is completely interchanged.

Inasmuch as it is possible experimentally to trace out only one set of these lines, it is very convenient by transposing the field to obtain the other. Very considerable use was made of this principle in making the experiments described in this paper.

The mathematical methods used in treating the problem involves the use of complex numbers such as $x+\sqrt{-1}\,y$ or $x+jy$; and more particularly the use of functions of these complex variables as representing the equations of the lines of force and the equipotential lines. The idea of giving a geometrical signification to the square root of a negative number is due to Argand[31], who suggested in 1806 that $X+jY$ or $X+\sqrt{-1}\,Y$ could be represented by a point with the co-ordinates X and Y.

The importance of the theory of complex numbers lies in the fact that, if we equate,

$$W = \phi + jV = F(X + jY) = F(Z) \qquad \textbf{(11)}$$

we obtain two functions of X and Y, that is ϕ and V, which are conjugate to each other.[32] Thus ϕ and V are related to each other as a two-dimensional flux function and potential function.

The properties of rational algebraic and trigonometric functions of a complex variable were familiar to Cauchy and Euler, but precise ideas of what constituted functionality were lacking until Rieman.[33] In 1799 Gauss[34] proved that all functions of a complex number were themselves complex numbers. Thus graphically, for every point (X, Y) in the Z plane there is a corresponding one (ϕ, V) in the W plane. Equation **(11)** can be thought of as transforming any figure in the W plane to a corresponding figure in the Z plane.

In 1822 Gauss[35] proved that the transformations effected by equations of the type of equation **(11)** were conformal; *i.e.* the angular relations were preserved and the corresponding infinitesimal parts of the two diagrams were similar. For instance in the equation,

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[31] Essai sur une manière de represente les quantities imaginaires dans les constructions geometrique.

[32] Rieman, Gessamelte Werke, p. 5, see also Webster, Dynamics of Particles and of Rigid, Elastic and Fluid Bodies, p. 522.

[33] Chrystal, Algebra 4th Ed. 1898, Vol. 1, p. 253.

[34] Gessamelte Werke, Vol. 3, p. 1.

[35] *ibid*, Vol. 4, p. 192.

$$t = \xi + j\eta = F\,(X + jY) \qquad \textbf{(12)}$$

we may regard the function $F\,(\;)$ as transforming an irregular conductor in the $(X,\ Y)$ plane into another conductor in the $(\xi,\ \eta)$ plane. These conductors are equivalent since the equipotential and flux lines in one conductor are all changed conformally in the new conductor; that is, without changing the shape of the enclosed cells of reluctance. In particular in equation (**11**), the lines in the Z plane formed by the lines $\phi = 0, 1, 2,$ etc. and $V = 0, 1, 2,$ etc. are small curved squares, and any rectangular conductor bounded by flux and equipotential lines is converted into an equivalent irregular conductor. If one tries a few simple functions of $(X + jY)$, and plots the curves of constant ϕ and V, he can quickly convince himself of the truth of the above statements. The importance of this principle to the theory of the reluctance of irregular magnetic fields, is that it furnishes a means of converting irregular into rectangular conductors, of which the reluctance is known.

In 1825 Gauss[36] showed that every conformal change could be represented by equation (**12**) provided only that the proper functions be found. This was equivalent to proving that every irregular conductor could be converted by this equation into an equivalent rectangular conductor. While it would be more convenient to make this conversion directly, it is generally found necessary to make the conversion in two steps through an intermediate irregular conductor equivalent to both. A conductor whose only boundary is an infinite straight line is found to be a most convenient intermediate form.

As a simple example of the use of the above method, let us take the function,

$$\phi + jV = (X + jY)^2; \quad \phi = X^2 - Y^2\,; \quad V = 2\,X\,Y.$$

The lines of flux and equipotential are mutually orthogonal hyperbolas. We can use this function therefore to find the reluctance of any figure bounded by these lines, such as that in Fig. 2. Thus

$$R = \frac{V_a - V_b}{\phi_p - \phi_o} = \frac{2\,X_a\,Y_a - 2\,X_b\,Y_b}{(X_p^2 - Y_p^2) - (X_o^2 - Y_o^2)}$$

$$= \frac{2\cdot 5\cdot 5 - 2\cdot 5\cdot(-5)}{(3^2 - 0^2) - (0^2 - 0^2)} = \frac{100}{9} = 11\,\frac{1}{9}$$

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[36] **Schumachers Astr. Abh. 1825, Ges. Werke, Vol. 4, pp. 189-216.**

From the point of view of equivalent conductors, the above equation may be said to convert the irregular conductor in Fig. 2 into the rectangle $V = 50$, $V = -50$, $\phi = 0$, and $\phi = 9$. The method illustrated by this problem has its limitations; for the proper function needed to suit a particular boundary is not always known.

The transformation of a polygonal area conformally into a half plane has been known since 1867, and is due to Christoffel[37] and Schwartz.[38] This is equivalent to converting a polygonal conductor into its equivalent conductor having a straight-line boundary. We are then able to find its reluctance easily by converting it a second time by the same theorem into a rectangle.

Let it be desired to convert the polygonal conductor shown in Fig. 3 into its equivalent conductor consisting of an infinite half plane with a straight line boundary. Let $Z = (X + jY)$ be the co-ordinates of any point in the polygonal conductor, and let $t = \xi + j\eta$ be the two rectangular co-ordinates of the corresponding point in the equivalent conductor with the straight line boundary. Then Schwartz's and Christoffel's theorem states that

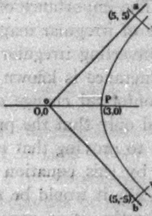

FIG. 2

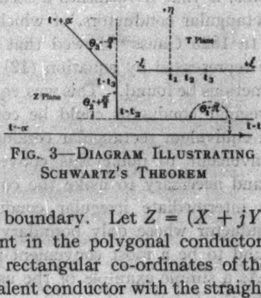

FIG. 3—DIAGRAM ILLUSTRATING SCHWARTZ'S THEOREM

$$Z = \int C(t-t_1)^{\frac{\theta_1}{\pi}} \cdot (t-t_2)^{\frac{\theta_2}{\pi}} \cdot \ldots (t-t_n)^{\frac{\theta_n}{\pi}} dt \qquad (13)$$

where θ_1, θ_2, etc., are the angles shown in the figure, being plus when measured toward the right and minus when measured to the left. The constants t_1, t_2, etc., at the corners of the boundary are the co-ordinates of the corresponding points in the straight line boundary of the t plane. Three of these constants are arbitrary, and the remainder are determined by the geometry of the polygonal conductor. The constant C determines merely the size and orientation of the equivalent conductor as a whole. There is of course another equation similar to equation (**13**) which transforms the conductor in the half t plane into a rectangular conductor in the W plane, whose co-ordinates are ϕ and V.

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[37] Annali di Matematica, Vol. 1, (1867), p. 89.

[38] Crelle, Vol. 70 (1869), p. 105. See also, J. J. Thomson, "Recent Advances in Electrictiy and Magnetism" p. 208.

When the equations of the lines of force and equipotential surfaces are desired, it is necessary to keep the signs and arguments of the various terms in equation (**13**) perfectly correct. When, however, the reluctance or resistance only of the irregular field is desired, without regard to the shape of the flux and equipotential lines, a simpler method may be used. In this case we integrate equation (**13**) without regard to argument, using only the moduli of the various terms, from one corner of the figure to another. In other words, the equation is integrated from t_1 to t_2, t_2 to t_3 etc. This method makes graphical integration possible.

The first use of Schwartz's and Christoffel's theorem for an electrical problem was made by Kirchhoff[39] who used it to determine the capacity of plate condensers. The first suggestion of using the method in magnetic phenomena is due to F. W. Carter,[40] who adapted Kirchhoff's and Thomson's results to the pole-tip fringing in an electric machine. J. J. Thomson[41] used the method in his book " Recent Advances" to find the capacity of the guard-ring electrometer and F. W. Carter[42] applied the result with some improvements to slot and air-duct fringing. The results are limited theoretically to the case of infinitely broad teeth, and infinitely deep slots. C. H. Lees[43] has determined the effect of a sudden change in the width of a conductor upon its resistance. He also found the effect of a narrow saw-cut on its resistance.[44] The writer has applied the method generally to check his experimental results. Since these computations are not included, it should be stated that the agreement was in all cases very close.

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[39] Monatsberichte der Akad. der Wiss. zu Berlin, Vol. 15, p. 144. See also J. J. Thomson, " Recent Advances" Chap. 3, Section 238.

[40] Inst. Elec. Eng. Jour. Vol. 29 (1900), pp. 925-933.

[41] Chap. 3, Sect. 241, p. 227; and Sect. 243, p. 233.

[42] *Electrical World and Engineer*, Vol. 38 (1901), p. 884. See also Inst. Civil Eng. Proc., Vol. 187 (1912), p. 311.

[43] *Phil. Mag.*, 5th Series, Vol. 16 (1908), pp. 734-739.

[44] Phys. Soc. Proc., Vol. 23 (Aug. 1911), pp. 361-366.

An application of this theorem to hydrodynamical problem has been made by Mitchell[45] and Love[46]. There are a few other more or less complicated cases where Schwartz's theorem has been applied, but these will not be quoted because they seem to be mostly of academic interest.

For irregular conductors bounded by circular arcs, reference may be made to Forsythe, "Theory of Functions," 2nd ed., Art. 271, p. 644. For the flux and potential problems in thin curved sheets, see Darboux, " Theorie General des Surfaces."[47]

The reluctance or resistance of irregular fields in three dimensions does not in general admit of solution. Indeed, there is not such thing as a flux function, except in a few cases. One of these is when the bounding surfaces and all the flux and potential lines are in surfaces of revolution. These cases are frequently met with in electrostatic problems, and therefore offer scope for future work along these lines. The following references are given to aid further study.[48]

Closely allied to the analytical method of conjugate functions is a graphical method due to L. F. Richardson[49] and to Dr. Th. Lehman.[50] It is quite fully developed by these authors for a two-dimensional field. It depends essentially upon the fact that the small square cells of such a field can be quite accurately drawn by the judgment of the eye, and also upon the fact that it is easy to adjust them correctly by the use of a pair of dividers. In this way various irregular fields can be drawn, and by counting the number of squares in series and in parallel, the reluctance of the field can be obtained. Mr. Richardson points out how the method may be used in the case of irregular fields bounded by surfaces of revolution, and also to the case of bodies made of a material showing saturation. Use was made of this method in drawing Fig. 26.

A very striking experimental method of determining the

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45. Phil. Trans. Royal Soc., 1890 part A, p. 389.

46. Proc. Camb. Phil. Soc., Vol. 7 (1891), p. 175.

47. Vol. 1, Book 2, Chap. 4, pp. 170, 176-180.

48. Stokes. " On the Steady Motion of Incompressible Fluids" Camb. Phil. Trans. Vol. 7, 1842: Math. and Phys. Papers, Vol. 1, p. 15. Sampson. " On Stokes' Current Function" Phil. Trans. 1891, Part A.

49. *Phil. Mag.*, Series 6, Vol. 15, Feb. 1908, p. 237.

50. E. T. Z. Vol. 30, (1909) pp. 995-1019. Lumiere Electrique, Vol. 8, No. 43, p. 403.

shape of the lines of force in a magnetic field is due to Hele-Shaw, Powell, and Hay[51], using the property that a viscous fluid in steady motion flows according to the same laws as an electric current. In order to render the stream lines visible, they injected thin lines of coloring matter. They controlled the permeability of the medium, by varying the thickness of the layer of fluid. They determined in this way the field resulting when cylinders, rings, toothed and shuttle armatures, and other variously shaped bodies are introduced into a magnetic field. They checked in this manner the theoretical work done by Carter.[52] They were followed by Dr. W. M. Thornton,[53] who used the method for determining the flux distribution in the armature cores of electrical machines. These plates are reproduced in a paper by Hansen before the A. I. E. E.[54] An application of the same method for determining the electrostatic fields in a three-phase cable has been made by Thornton and Williams.[55]

In order to use the above method to determine the actual reluctance of an irregular field of force, measurements were made of the pressure of the liquid supply, the quantity of flow, and the coefficient of viscosity.

The most useful experimental method of determining the reluctance of irregular magnetic fields, is to make use of the similarity of the electric and the magnetic circuits, and measure the resistance of the corresponding irregular electric circuit.

Kirchhoff[56] was the first to propose determining the equipotential lines and resistances of an irregular two-dimensional electric current field, by the use of a specially cut sheet of metal and specially fastened electrodes. Application of the method to other cases was made by G. Carey Foster and Sir Oliver Lodge[57] in 1875, who gave a good bibliography of this part of the subject. Gaugain[58] modified this method by using liquid conductors such as mercury, zinc sulphate, and copper sulphate. W. G. Adams[59] developed Kirchhoff's method, making suitable for three dimensions, and using liquid instead of solid conductors.

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[51] *Electrician* (London), Vol. 54, Nov. 25, 1904, p. 213. Phil. Trans. Royal Soc. Vol. 195, 1900 Part A, p. 303-327.

[52] *Electrical World and Engineer, Loc. Cit.*

[53] Jour. Inst. Elec. Eng., Vol. 37 (Feb. 26, 1906), p. 125.

[54] A. I. E. E. TRANS. Vol. 28, June 30, 1909, pp. 993-1001.

[55] *Engineering*, Vol. 88, Aug. 27, 1909, p. 297.

[56] Poggendorf's Annalen, Vol. 64 (1845), p. 497.

[57] Proc. Phys. Soc. of London, Vol. 1, pp. 113-193.

[58] Ann. de Chemie et de Physik, No. 3, Vol. 64, 1862, p. 200.

[59] Proc. Royal Soc. 1875, Vol. 23, p. 280.

The use of an electrical experiment upon thin sheets of an electrical conductor, for determining the reluctance of the corresponding magnetic fields was proposed by F. W. Carter[60] in 1901. He himself, however, used only the mathematical method. He also proposed the use of the conjugate character of the flux and potential functions to determine the shape of the lines of force. Since a millivoltmeter can only be used to trace equipotential surfaces, if we desire to trace lines of flow, we must contrive to interchange the two sets of lines. Mr. Carter proposed cutting a metal strip, to the shape of the desired irregular magnetic field, but to solder the electrodes to those parts of the boundary which were flux lines. The remaining or desired equipotential portions of the boundary were to be left free. In this way, an interchange of the roles of flux and potential functions is secured upon the boundary, and consequently throughout the rest of the strip also.

The suggestions of Mr. Carter were first carried out by Mr. C. H. Smoot[61], who used the method to check experimentally the reluctance of a case solved theoretically by Mr. Carter. He applied the method, also, to get the flux distribution in the air gap of an alternator. Both suggestions of Mr. Carter were used by the writer in the tests described in this paper.

An application of the similarity of the electric current field to the electrostatic field, has been made in 1913 by Fortescue and Farnsworth[62], who used a three-dimensional electrical model of various irregular electrostatic fields. Recently R. Forster[63] has developed a method of determining the electrostatic field which he applied to a three-phase cable. He used a conducting liquid, and to avoid polarization, inverted the functions of the galvanometer and battery circuit of a Wheatstone bridge. The method seems to have points of similarity to one of those used by G. Carey Foster and Sir Oliver Lodge.[64]

III. Description of Experiments

In order to determine the reluctance of various irregular magnetic fields, use was made of the similarity of the electric and the magnetic circuits, and of the conjugate character of the flux and potential lines. The resistances of various irregular sheets of metal were measured upon an apparatus shown in Fig. 4, and the equipotential lines were also traced out. This was done to determine the permeance of the similar magnetic field, and the shape of the lines of force.

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[60] *Electrical World and Engineer, loc. cit.*

[61] Jour. Western Soc. Eng. Vol. of 1905, p. 500.

[62] A. I. E. E. Trans., Vol. 32, Part I (1913), p. 893.

[63] *Archiv fur Elektrotechnik*, Vol. 2, 1913, No. 5, pp. 175-180.

[64] Proc. Phys. Soc. of London. *Loc. Cit.*

Measurement of the resistance consisted in setting the stylus attached to the terminals of the millivoltmeter alternately on the two points between which the resistance was desired, and adjusting the terminal on the slide wire for a null reading. This was easily done, as the millivoltmeter had a zero center, and both a ten and a hundred millivolt scale. Readings were taken of the two ammeters and of the settings upon the slide wire.

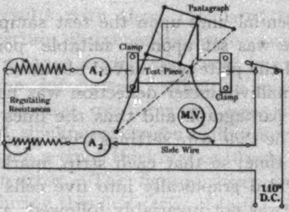

Fig. 4—Diagram of Connections Used in Experiments

The main current and the current in the slide wire were maintained constant to suit frequent calibration tests. Since the absolute resistance was not desired, but only the geometric resistance, calibration of the meters was not made. The calibration of the slide wire was effected checking it against a regular or rectangular sample cut from the same sheet as the irregular sample, and ruled into exact squares. In this way identical thickness was secured between the irregular sample and the sample for calibration. The current in the slide wire was adjusted so that the drop in twenty centimeters was twenty millivolts. This current was held rigorously constant. The main current was adjusted carefully at each calibration so that the drop in one square of the calibration sample was equal to that of approximately twenty centimeters upon the slide wire. In any case the exact drop in the calibration sample K was noted. In other words a drop of K centimeters on the slide wire was equivalent to one unit of geometric resistance or reluctance both in the regular calibration sample, and the irregular sample for testing. Thus to find the resistance between two points 1 and 2 at which the slide wire settings were V_1 and V_2, we divide the difference of the settings by K.

Direct deflection of the millivoltmeter was not used, except when, under special circumstances, a range beyond that of the slide wire was required. For this reason a drop of twenty millivolts per twenty centimeters of slide wire was chosen so as to make extrapolation easy.

In most of the problems investigated it was desired to determine the shape of the lines of flux, while the millivoltmeter could only trace equipotential lines. Hence the roles of the flux and equipotential lines was transposed, by fastening the electrodes to only those parts of the boundary which, in the magnetic problem, are flux lines. In this way the millivoltmeter can be used to trace the flux lines. The resistance, as measured in this way, is really the geometric conductance or permeance of the problem which it is desired to study. Thus we have for computing the permeance the equation

$$P = (V_1 - V_2)/K \qquad . \mathbf{(14)}$$

In tracing out the equipotential lines upon the test sample, the slide upon the slide wire was set upon a suitable point and the stylus which touched the plate was moved about so as to find points for which the millivoltmeter deflection was null. The stylus was carried by a pantagraph and thus the lines of force were drawn at once. The slide wire settings were usually varied four centimeters at a time; so that each strip, marked off in this way, could be divided graphically into five cells of square shape. However this was not invariably followed; and always at any singular point, such as at a corner, an extra line was traced. While experiments were in progress, the use of a pantagraph for tracing equipotential surfaces was described by Fortescue and Farnsworth in their A. I. E. E. paper mentioned above.

The metal selected for testing was an alloy made by the Driver-Harris Co. by the name of "therlo." The sheets were approximately 10 mils thick. ($\frac{1}{4}$ mm.). The specific resistance was approximately 40 michrohms per centimeter cube. This metal was selected because of its high specific resistance, small temperature coefficient, and low thermoelectric power when used with copper.

The first tests were made to test for thermal effects, which were found to be negligible. The samples were clamped between heavy copper terminals, projections having been left upon those edges of the sample which it was desired to maintain at a constant potential.

The next tests were made to determine the effect of contact resistance drop between the test sample and the copper clamps. The drop was found to be considerable and steps were taken to reduce it. First the copper terminals were cleaned with emery cloth, and then partly amalgamated. The drop was reduced in this way considerably, so that regular tests were begun. In order not to include the contact resistance drop the potential was read upon the therlo sheet, but very close to the copper electrodes. To facilitate this work, a fine line was ruled upon the metal sheet on which the potential was desired, The copper electrodes were then clamped very near and parallel to this line.

It was noted, in cases where the clamps were so placed that the current entered the metal sheet non-uniformly, that the potential along the desired equipotential line varied, because of a varying contact resistance drop. Upon comparing the results with those calculated from the mathematical theory, certain discrepancies were discovered. Search was made for constant errors, and found in excessive contact resistance, and too infrequent calibration samples. Also, in certain cases, thickness measurements were made rather than the equality of thickness between calibration and test samples secured. In such a small thickness as 10 mils, this was of necessity somewhat in error. The figures shown in this paper were mostly taken during this first series of tests. It is believed, however, that the shape of the lines of force are substantially accurate, even if the spacing between them is only approximate.

In the second series of tests a rectangle was cut from every irregular shaped template after it was tested; and this rectangle was used for calibration. Owing to the large number of tests made it did not seem desirable to solder the electrodes directly to the therlo sheet in order to secure a low contact resistance, because, in each sample tested, the electrode was cut to a smaller size several times. The following compromise proved to be very satisfactory. Thin strips of copper about five mils thick were soldered to the test sample accurately adjacent to the line on which the potential was desired. This combination was clamped between the heavy electrodes. The double thickness of therlo and copper was easily cut. Not only was the contact drop greatly reduced in this way, but the highly conducting copper strip served to redistribute the current before it entered the therlo test sample. Even when the current entered the therlo sheet more in some places than in others, the voltage setting along the desired equipotential line hardly varied at all. This was in marked contrast to the first series of tests. In this way not only was the difficulty of contact resistance overcome, but in such a manner that the work was rapidly clamped, measured, unclamped, cut to a new size, and occasionally resoldered.

A few irregular test pieces were measured and found to give results in complete agreement with the mathematical theory. It was believed then that the constant error was eliminated. In one of the last series of tests, it became necessary to solder several sheets of therlo together, in order to obtain a template of sufficient size. Owing to warping and the presence of oxide the seam had to be very wide, and the sample was, therefore, heterogeneous. As a consequence some constant error in these tests is to be expected. Fig. 25 shows the arrangement in this case, together with the method adopted in laying out an irregular template and trimming it to size.

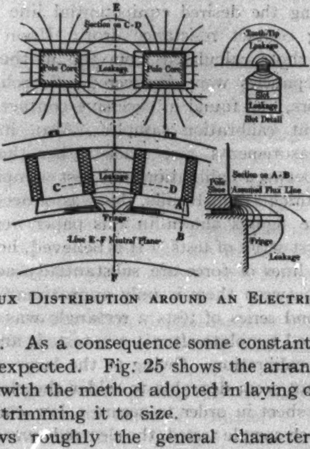

FIG. 5—FLUX DISTRIBUTION AROUND AN ELECTRIC MACHINE

Fig. 5 shows roughly the general character of the lines of force around a multipolar electric machine. It is apparent that the lines of force are not parallel to any one plane, except perhaps in the air gap. Nevertheless the sketch suggests various irregular two dimensional fields, which are at least approximations to the actual field. In Fig. 6 is shown the various subdivisions of the field of an electric machine, which result from imagining the lines of force guided by certain surfaces. At the right is shown the best assumptions as made at present, while at the left is shown another method, which will be shown in a later paragraph to be more accurate. It will be noted that the assumptions made in the figure at the left reduce the various sections of the field to two-dimensional flux distributions, suitable for treatment by the methods outlined. Another point of interest is that the figure at the right shows some obvious sources of error; namely, in two places two kinds of flux are supposed to occupy the same space at the same time, and also the field is the more cramped of the two. In the experimental work the shapes of the irregular magnetic fields shown in Fig. 6 at the left were systematically taken up and studied. In addition a few extra topics of some interest suggested themselves as the work progressed and were investigated.

The effect of the slots and teeth upon the value of the air-gap reluctance has been partially investigated by F. W. Carter and reported in the *Electrical World*.[65]. He assumed infinitely deep slots, and infinitely wide teeth, and neglected the effect of the notches cut to receive the wedges. These factors are reported on here.

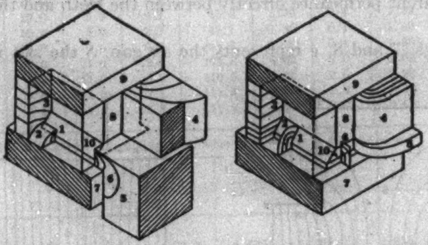

Fig. 6—Subdivisions of the Field of an Electric Machine

1—Pole tip fringe
2—Pole tip leakage fringe
3—Pole side leakage
4—Pole flank leakage
5—Pole shoe flank leakage
6—Pole shoe flank fringe
7—Armature core
8—Pole core
9—Pole yoke
10—Pole shoe and pole tip

In Figs. 7 and 8 is shown the flux distribution in the air gap of a slotted armature. The sample of sheet metal for testing was cut in the form shown by the letters *a*, *b*, *c*, *d*, *e*, *f*, the electrode being soldered to the strip at the lines *ab* and *de*. When the current was passed through the strip, the curved lines of force were traced out by the pantagraph as shown. The measured resistance gave the permeance of the flux from the tooth ends and that in the tooth fringe combined. Since this combined permeance depends upon the tooth width, $2x$, we usually desire to find the excess or fringe of this permeance. That is, the fringe permeance is the amount that the total permeance is in excess of that which might be expected to pass from the ends of the teeth, under the assumption that the lines of force were all radial. In Fig. 7 the permeance of the fringe is calculated from experimental values by the formula,

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[65] *Loc. cit.*

$$P_f = \frac{V_e - V_a}{K} - \frac{2x}{g} \tag{15}$$

Here $(V_e - V_a)/K$ is the total measured permeance, and $2x/g$ is the apparent permeance directly between the teeth and the pole surface.

In Figs. 7 and 8, g represents the air gap, S the slot width,

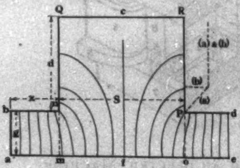

FIG. 7—TOOTH FRINGE FLUX FOR SMALL AIR GAP

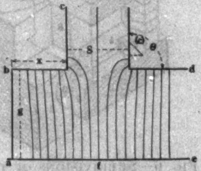

FIG. 8—TOOTH FRINGE FLUX FOR LARGE AIR GAP

D the slot depth, θ the angle between the tooth side and end. In general, the symbols used will be clear from reference to the figure. The dotted lines labeled a, b and c represent three shapes of notches cut to receive the slot wedges. These notches in the test pieces were cut to a depth of 20 per cent of the slot width on each side.

Some of the data together with computations are shown in Table I; the results are plotted in Fig. 9. In addition the effect of the depth of the slot, and the inclination of the tooth tip were studied and these results plotted in Figs. 9 and 10.

It is to be noted, that the effect of the depth of the slots is negligbile until the depth is less than the width. Also, it is apparent that the presence of a notch has little effect unless the tooth tip forms an angle less than 90 deg. The data for the other cases studied were worked up in exactly the same way, and will not be included in this paper.

TABLE I.

DATA AND COMPUTATIONS FOR DETERMINING FRINGE PERMEANCE FROM TEETH.

CALIBRATION:

Meter A_1 read 12.0 amperes, Meter A_2 read 32 millivolts.
Drop in one square of calibration sample equaled 19.95 centimeters drop on slide wire.
Thickness of sample 9.6 mils.

TEST DATA AND COMPUTATIONS.

(1) Effect of shape of armature slot, when $D > S$ and $x = 1$.

Shape	S	g	V_a	V_g	$\frac{V_g - V_a}{19.95}$	$\frac{2x}{g}$	P_f	$\frac{S}{g}$
(a)	10.0	5.0	9.9	44.4	1.71	0.400	1.31	2.0
(b)	10.0	5.0	9.7	45.5	1.79	0.4	1.39	2
(c)	10.0	5.0	9.7	45.7	1.80	0.4	1.40	2
(d)	10.0	5.0	9.6	45.7	1.805	0.4	1.405	2
(a)	7.0	1.0	12.2	105.8	4.69	2.0	2 69	7.0
(b)	7.0	1.0	12.6	110.5	4.90	2.0	2.90	7
(c)	7.0	1.0	13.1	111.3	4.93	2.0	2.92	7
(d)	7.0	1.0	13.8	112.2	4.03	2.0	2.93	7

(2) Effect of depth of armature slot, when $S/g = 8$, $S = 10$, and $x = 1$.

D	g	V_a	V_g	$\frac{V_g - V_a}{19.95}$	$\frac{2x}{g}$	P_f	$\frac{D}{S}$
15.0	1.25	12.5	103.2	4.535	1.60	2.935	1.50
5.0	1.25	12.1	105.2	4.650	1.60	3 050	0.50
2.5	1.25	12.3	113.7	5.070	1.60	3 470	0.25

NOTE: Shapes *a*, *b* and *c* refer to the shapes of the tooth-tip shown in Figs. 7 and 8. Shape *d* is rectangular pole tip without any notch cut for the slot wedge.

The curve in Fig. 9 for infinitely narrow teeth, and that in Fig. 10 for various depths of slots, were obtained mathematically and not experimentally. It is interesting to note that whether the teeth are infinitely wide or infinitely narrow the fringe permeance is nearly the same. Experimental results for moderately wide teeth agreed more closely with the curve for infinitely wide teeth.

The practical effect of the slots is to increase the air-gap reluctance, or to decrease its permeance. We may think of the effective area of the flux as decreased, and the ratio of this decrease as the air-gap factor K_a.

The effective area is very readily computed from the curves of permeance in Figs. 9 and 10, by multiplying the permeance

P_f by the air gap g to get the amount to be added to the width of each tooth for fringing.[66] Analytically the tooth fringe Δt is

$$\Delta t = P_f \times g \tag{16}$$

On the other hand, we may think of the average length of the lines of force in the air gap as increased in the ratio K_a.

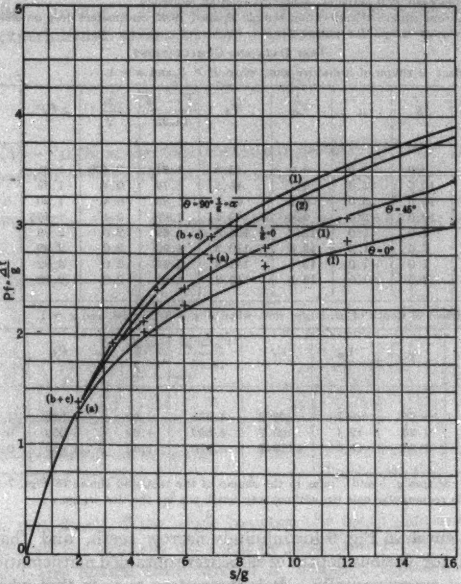

FIG. 9—FRINGE PERMEANCE FROM SIDES OF TEETH TO ARMATURE (DEEP SLOTS)

1. Infinitely wide teeth. 2. Infinitely narrow teeth.

This point of view is perhaps the most helpful when the air gap is long, for two reasons. In the first place, with a long air gap the ratio of S/g is small and Figs. 9 and 10 are inaccurate. In the second place, a theoretical investigation showed that the width of the tooth had an important effect in this case while the size of the air gap was unimportant. The results of this investigation are shown in Fig. 11. The excess length to be added to the air gap is obtained by taking the reluctance R from the curve and multiplying it by the tooth pitch, λ. Analytically the excess air gap with Δa is

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[66] For example see Karapetoff, " Magnetic Circuit", Chap. 5, p. 93.

$$\Delta a = R_e \lambda \tag{17}$$

That the width of the teeth has an important effect upon the air gap reluctance for long air gaps, is seen by comparing with the approximate curve also shown in Fig. 11. This approximate curve was calculated from the formula for Fig. 9, curve 2, for a small ratio of S/g.

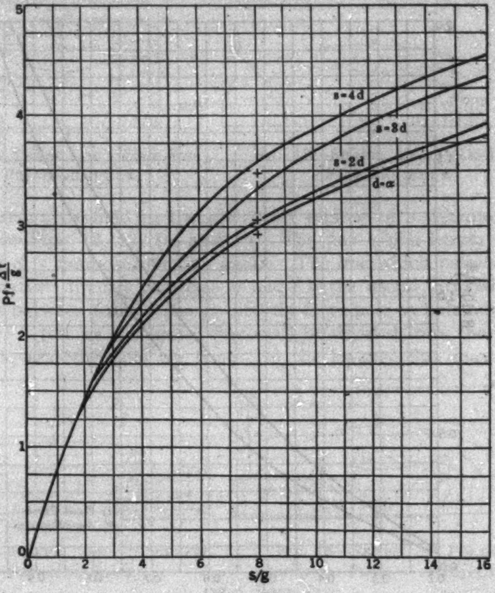

FIG. 10—FRINGE PERMEANCE FROM SIDES OF TEETH TO ARMATURE, FOR T/G = O

The case of the air gap of an induction motor is one that proved too difficult for the writer's power of analysis. However, it is a case that might well be studied from the experimental side. It has been partly solved by F. W. Carter,[67] in a footnote of an article on Magnetic Centering of Electrical Machinery.

The various approximate formulas for air-gap factor are now of little interest; a short bibliography, however, is given.[68]

Because of desired economy of space a detailed description of each experiment will not be given. In each case the shape of the template cut for testing can be seen by referring to the figure giving the shape of the lines of force. The portion outlined by the letters *a*, *b*, *c*, *d*, *e*, *f* in each case gives the shape of the test

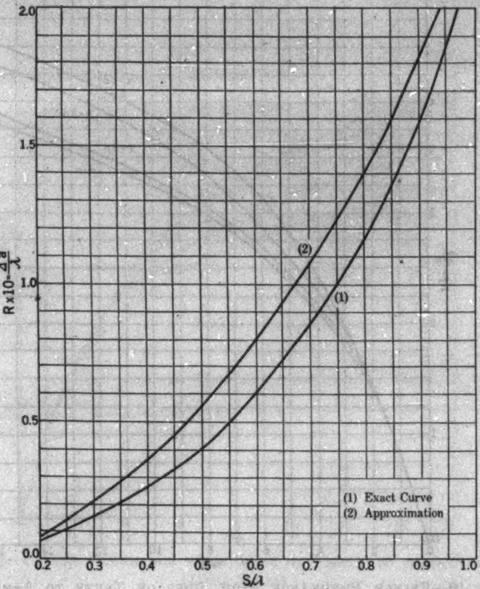

FIG. 11—EXCESS RELUCTANCE OF AIR GAP FOR EXTRA LONG AIR GAPS

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67. Proc. Inst. Civil. Eng. Vol. 187, (1912), p. 311.

68. Guilbert, Ind. Electrique, Vol. 9, (1900), pp. 377-379. Muller, E. T. Z., Vol. 1906, Vol. 27, p. 1103. Wall, Inst. Elec. Eng. Jour., Vol. 40, pp. 550-568. Baillie, Electrician (London), Vol. 62, (1909), p. 494. Rezelman, Lumiere Electrique, Vol. 11, (1910), p. 202.

piece, the electrodes being soldered to the lines *ab* and *de*. In each case data were taken in a form similar to Table I, and the permeance calculated in the same manner. In all cases the curves of permeance were calculated by means of the mathematical method as well as the experimental method, and in all cases the results were found to agree very closely. Any special features differing from the above are specially mentioned.

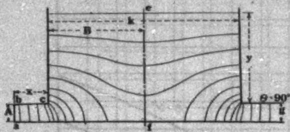

FIG. 12—SHAPE OF POLE-TIP FRINGING FLUX

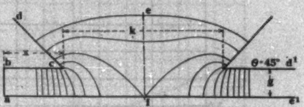

FIG. 13—SHAPE OF POLE-TIP FRINGING FLUX

The magnetic field in the interpolar regions of a dynamo is shown in Figs. 12, 13, 14, and 15. The flux which leaves the pole *b c d* is composed of two parts. The one which passes to the armature directly between *a* and *f* is the useful flux, while the rest between *f* and *e* passes directly from pole to pole and is leakage. Just as the useful flux may be divided into the air gap flux, and the pole tip fringe, so the leakage flux may be divided into the pole side leakage (calculated) as if passing directly from one pole to the other) and the remainder which may be called the pole tip leakage flux. The pole tip fringe may be calculated from the experimental data by the formula

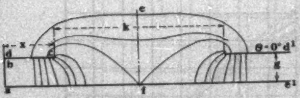

FIG. 14—SHAPE OF POLE-TIP FRINGING FLUX

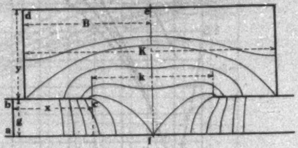

FIG. 15—SHAPE OF POLE-TIP FRINGING FLUX, PROJECTING POLE-TIPS

$$P_f = (V_f - V_a)/K - (x/A) \qquad (18)$$

The pole tip leakage fringe may likewise be calculated by the formula

$$P_{lf} = (V_e - V_f)/K - (y/B) \qquad (19)$$

Here V_a, V_f, and V_e are the slide wire readings at the points a, f and e as shown in the figures, and K is the calibration constant.

The values of the pole-tip fringe permeance are plotted in Figs. 16 and 17 and that of the pole-tip leakage permeance in Fig. 18. It is interesting to note that the curves for pole-tip fringe, are similar in shape to those for tooth-tip fringe as in Fig. 9 except for a constant difference of 0.88: this is easily proved by the mathematical method given above. An approximate curve used frequently at present is that of Hawkins and Wrightman[69] given at top of Fig. 16. The effect of pole tip fringing is practically to increase the pole face width W by an

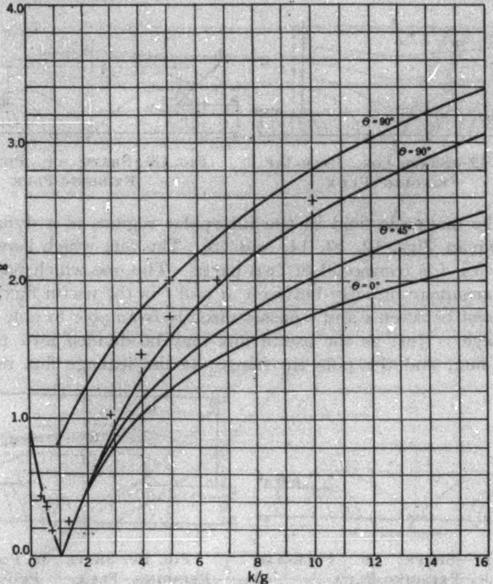

FIG. 16—PERMEANCE OF FRINGE FLUX FROM POLE-TIPS TO ARMATURE

amount Δ *W* in all, or one half that amount at each pole tip. This fringe is obtained from curves in Figs. 16 and 17 by multiplying the ordinates by the air gap *g*. Analytically,

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[69] Inst. Elec. Eng. Jour., Vol. 29, pp. 436.

$$\Delta W = P_f \, g \tag{20}$$

The occasional negative value for the pole tip leakage in Fig. 18 really indicates that the pole tip fringing encroaches so far on the pole tip that the leakage flux is actually decreased thereby. Thus the error which is committed in Fig. 6 at the right, in assuming two different fluxes in the same place, is rendered plain. The amount to be added to the length of each pole to allow for this pole tip leakage is obtained by multiplying

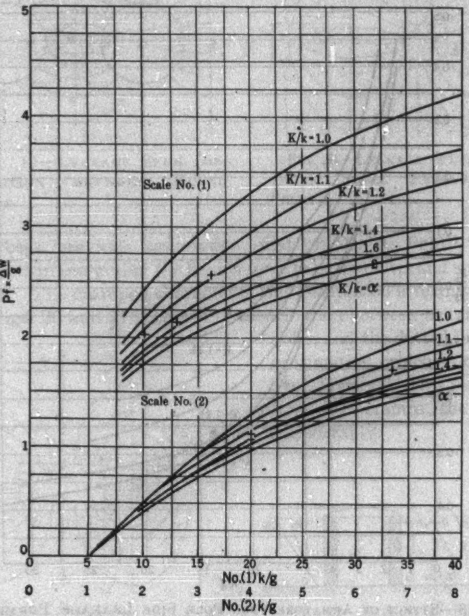

FIG. 17—FRINGE PERMEANCE FROM POLE-TIPS TO ARMATURE, $\theta = 0$

the ordinate of Fig. 18 by K, the distance between the pole cores nearest to the air gap. Or, expressed analytically,

$$\Delta H = P_{lf} K \tag{21}$$

By referring to Fig. 5 it will be seen that some of the leakage flux passes directly from the pole core to the pole yoke. This path is shorter than that assumed from the pole core to the neutral plane. As a consequence the permeance of the leakage flux is somewhat increased. Study of a field of flux somewhat similar by the method of complex quantities has indicated that this effect can be allowed for by adding to the length of the pole a fringe ΔH, which is approximately

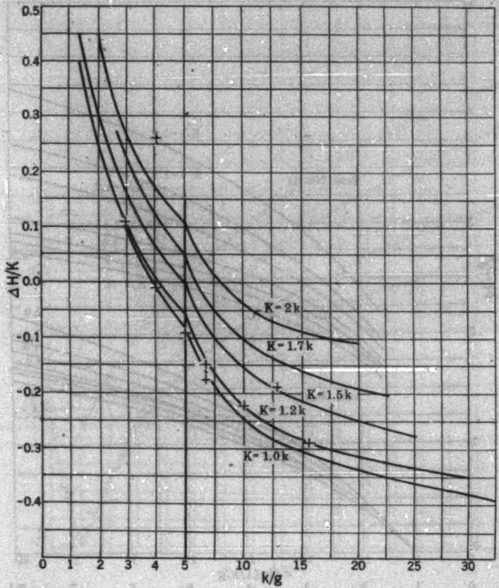

Fig. 18—Effect of Armature upon Pole Side Leakage Permeance

$$\Delta H = 0.3\, A^2/H \tag{22}$$

Here A is half the distance between the poles, and H is the length of the poles.

The distribution of leakage flux between circular poles of a multipolar machine is given in Fig. 19. The dotted lines give the best previous assumption, that of Dr. R. Pohl[70], which consists in imagining the lines of force to be involutes and straight lines. The cramped character of this assumption is readily seen. In Figs. 20 and 21 is shown the distribution between rectangular poles, and the dotted line approximation which is due to Prof. Forbes.[71] This assumption also cramps the field considerably.

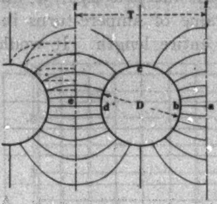

FIG. 19—LEAKAGE FLUX DISTRIBUTION BETWEEN ROUND POLES

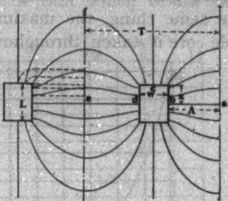

FIG. 20—LEAKAGE FLUX BETWEEN SMALL RECTANGULAR POLES

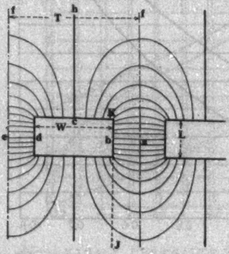

FIG. 21—LEAKAGE FLUX BETWEEN LARGE RECTANGULAR POLES

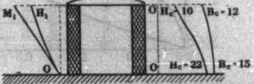

FIG. 22—EFFECT OF LEAKAGE UPON FLUX AND M.M.F. IN POLE CORES

The effect of leakage upon pole saturation is shown graphically in Fig. 22. The free m.m.f. between the poles and the flux density in the interpolar regions, is shown at the left.

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[70] Jour. Inst. Elec. Eng., Jan. 1, 1914, Vol. 52, p. 120.

[71] Jour. Soc. Teleg. Eng. and Elec., Vol. 15, (1886), p. 551. See also Hawkins and Wallace, "The Dynamo", 3rd. Ed. p. 437.

Methods allowing for this effect are well known[72] and consist of counting only one-half of this leakage permeance as effective. The variation of the flux and ampere-turns in the pole core are shown at the right, both varying greatly. At present it is assumed that all the leakage enters at the pole tips; or, what is the same thing, the maximum value of ampere-turns in the pole core is taken throughout its entire length. It would be better to assume the leakage flux to enter the core at some point nearer the pole yoke, say one-half way up. The exact location could be determined by a graphical integration similar to that given by W. B. Hird[73] for the case of the reluctance of tapered and saturated armature teeth.

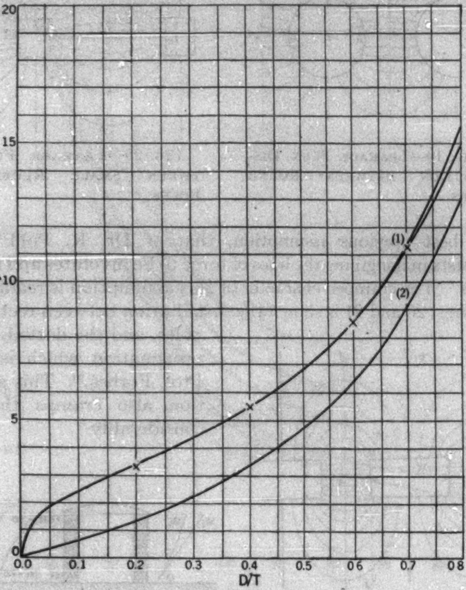

FIG. 23—LEAKAGE PERMEANCE FROM ROUND POLES TO NEUTRAL PLANE
1—Exact solution 2—Approximate solution

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[72] Hawkins and Wallace "The Dynamo", 3rd. Ed., p. 441. Pohl, Jour. Inst. Elec. Eng., *loc. cit.*

[73] Jour. Inst. Elec. Eng. Vol. 29, p. 939.

The values of the leakage permeance from round poles to the neutral plane are plotted in Fig. 23, together with that calculated from Pohl's formula. The flux which leaves rectangular poles, as in Fig. 21, between the points *b c d*, may be considered as divided into two parts. The first is that which would pass directly between the poles if the lines of force were straight; this is the pole face leakage. The remainder is fringe of the leakage flux, or what is called elsewhere the pole flank leakage. The formula for computing this leakage from the data is similar to equations (**15**), (**18**) and (**19**), and will not be given here. The result is plotted in Fig. 24, together with the customary ap-

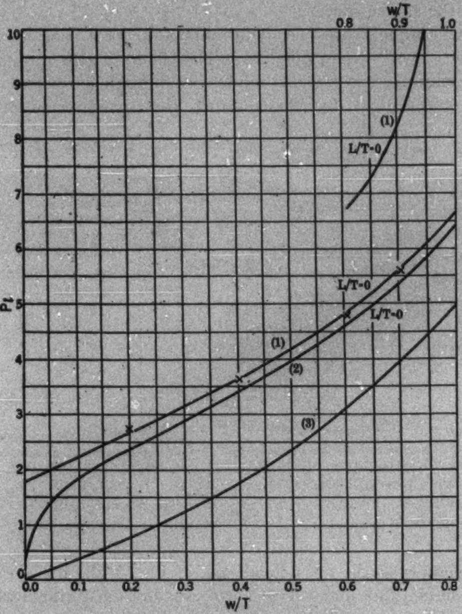

Fig. 24—Leakage Permeance from Rectangular Poles to Neutral Plane, in Excess of that between the Poles
(1) and (2) exact solutions—(3) approximate solution

proximate formula. In order to compute the leakage we multiply the ordinate taken from Fig. 24 by H, the length of the poles, increased ΔH for fringing at the roots, but not at the tip. It is to be noted that, except for very short machines axially, the upper of the two curves in Fig. 24 is the nearer the truth. In all cases the experimental data agreed closely with the upper curve.

The template used for determining the pole shoe flank permeance is shown in Fig. 25. This figure shows the method of trimming so as to get a number of different proportions with one sample. In Fig. 26 is shown the flux distribution; this corresponds to the right-hand part of Fig. 5, the line *d e* being an assumed flux line. This figure was obtained graphically by the method of L. F. Richardson, given above. Lines 2, 4, and 6, and 9, 11, 13, etc., were drawn first. Then lines 1, 3, 5, 7, 8, 10, 12, etc., were drawn to test the accuracy of the preceding lines. For instance, in the square 4, 6, *s*, *u* the line *p r* was compared with the line *s t* for equality. Considerable readjustment was necessary, and the reader will no doubt note improvements.

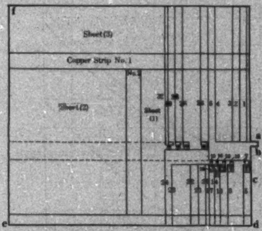

FIG. 25—METHODS OF MARKING AND CUTTING TEMPLATES OF SHEET METAL TO SIZE, SO AS TO ECONOMIZE MATERIAL

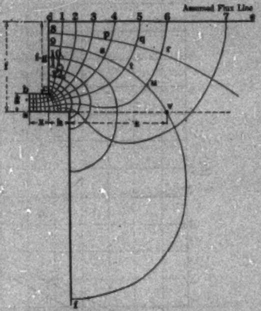

FIG. 26—DISTRIBUTION OF FLUX IN THE FRINGE FROM THE POLE FLANKS TO THE ARMATURE—DETERMINED GRAPHICALLY

The flux leaving the pole in Fig. 26 between the points *b c d* may be divided in the usual way into air-gap flux, and the fringe flux. The formula for computing this from the data is similar to equations (**15**), (**18**) and (**19**). In this way the permeance in Figs. 27 and 28 was computed and plotted. It will be seen that this permeance depends on both the ratio of *f* to *g* and of *h* to *g*. This permeance, it is to be noted, is the combined pole shoe flank flux, both useful and leakage flux; and includes flux on both ends.

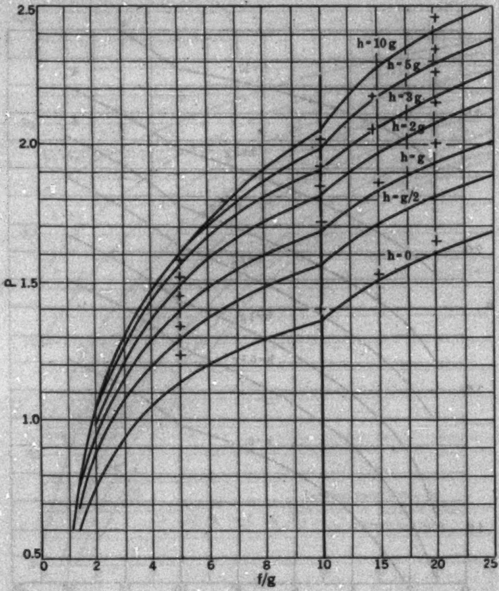

Fig. 27—Permeance of Fringe Flux from Pole Flanks to Armature Surface—For an Overhanging Armature, *i. e.*, Longer than Poles

It will be noted that the point *v* on line of flux No. 9 in Fig. 26, is also on the dotted line which is the projection of the armature coils. Thus the point *v* may be regarded as the trace of the armature coils. The flux between the line 9 *v f* and the armature links with the armature coils, and is useful. The flux between the line of 9 *v f* and the line *d e* is really leakage flux. Readings of the slide wire setting V_s were taken at various points shown on the dotted lines in Figs. 25 and 26, located at a distance *z* from the armature corner. The fraction of the total pole shoe flank flux that is useful was calculated by the formula

$$\frac{P_u}{P} = \frac{(V_z - V_a)/K - (x/g)}{(V_c - V_a)/K - (x/g)} \qquad \textbf{(23)}$$

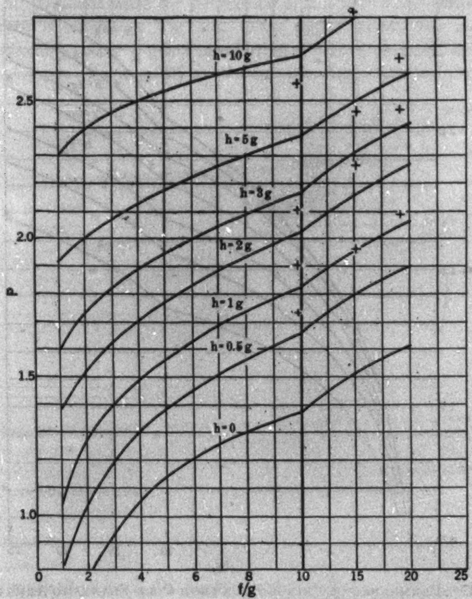

FIG. 28—PERMEANCE OF FRINGE FLUX FROM POLE FLANKS TO ARMATURE —FOR OVERHANGING FIELD POLES

This fraction was computed and plotted in Fig. 29. While this fraction theoretically should be a function of three variables, it was found it did not depend much upon the ratio of *f* to *g*. This rather fortunate coincidence permitted the results to be plotted in a single set of curves. Fig. 29 was not checked theoretically.

It is to be noted that the line *d e* is an ***assumed*** flux line. There is no natural boundary between the leakage lines and the fringe lines, and hence the point *d* has to be assumed in a somewhat arbitrary manner. Several rough trials have convinced the writer that the best location for the point *d* is at the junction of the pole shoe with the core, or at one-quarter to one-third

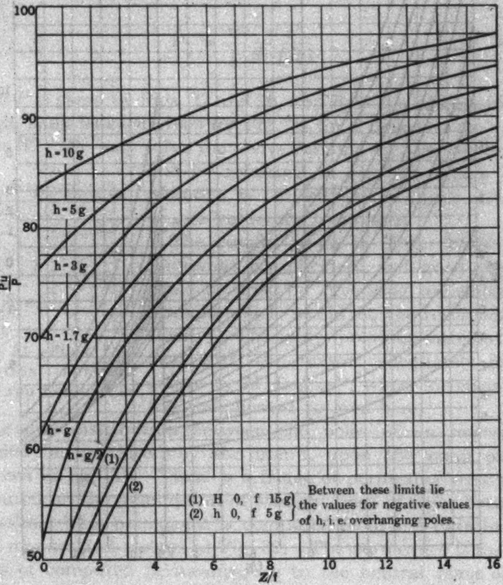

FIG. 29—CHART SHOWING THE PERCENTAGE OF THE POLE-FLANK FRINGE THAT IS USEFUL, FOR VARIOUS LOCATIONS OF THE ARMATURE COILS

of the width of the pole waist from the armature. Rough as this method is, it is hoped that it will be useful; a more accurate assumption is discussed in a later paragraph.

In order to use Figs. 26, 27 and 28 we first estimate the width *f* of the pole shoe flux by the method of the preceding paragraph. From the working drawing of the machine we compute the ratios *h*/*g* and *f*/*g*, and from either Fig. 27 or Fig. 28 obtain the flank permeance. This we divide in two parts by means of Fig. 29, into the pole shoe flank fringe P_u and leakage, P_{lf}. The effect of the fringe is to add to the effective axial length of the air gap by an amount ΔL which is given by the equation

$$\Delta L = P_u\, g \tag{24}$$

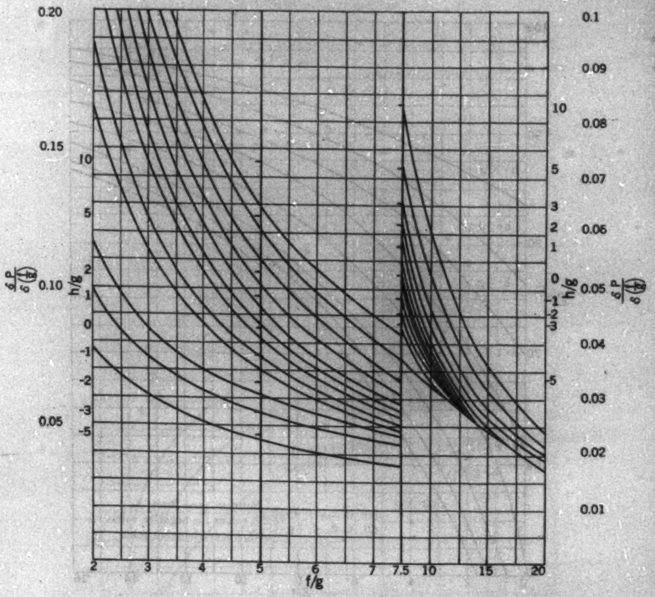

FIG. 30—CHART FOR DETERMINING WIDTH OF POLE FLANK FRINGE

The effect of the leakage fringe is to add to the leakage permeance by an amount

$$P = P_{lf}\,(W + \triangle W), \tag{25}$$

where $W + \Delta W$ is the corrected width of the pole shoe next the armature.

The principle of "maximum effect" can be applied to the results given in Figs. 27 and 28, enabling one to pick out the most favorable value of the width of the pole shoe flank flux, f. This principle states that of two possible assumptions as to flux, that is nearer the truth which is the larger. Fig. 30 is the result of an attempt to apply this principle to the problem. For a maximum total permeance, the derivative of the pole shoe flank permeance with respect to f should be equal to that of the leakage permeance, taken with the minus sign. In symbols,

$$P_l = \frac{w}{g} \frac{d\,P}{d\,(f/g)} \tag{26}$$

where P is given by Figs. 27 and 28, and P_l is the leakage fringe or pole flank leakage given by Fig. 24 for a definite pole waist width W. We may solve the above formula for the derivative, and by referring to Fig. 30 where this quantity is plotted, we can pick out the proper value of f/g at once.

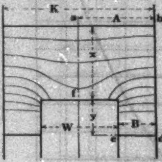

Fig. 31—Flux Distribution between Main and Interpoles

The results given in Figs. 27–30 are somewhat complicated, and good service could be done by inventing an empirical formula which would fit the results fairly closely. The only previous attempt to deal with the matter adequately is an article by M. Legros[74], whose formulas are too complicated to give here.

The flux distribution between the poles of an interpolar machine (as produced by the m.m.f. upon the main poles) is shown in Fig. 31. There is a fringe of permeance over that computed on the assumption of straight lines of force between the poles. This permeance is computed from the data in the usual manner and plotted in Fig. 32. The permeance is that in excess of computed permeance, up to the neutral plane only, for both ends of the interpoles and for two interpoles.

The leakage flux distribution inside a slot is shown in Figs. 33 and 34. The template cut in this case is similar to that cut for the preceding case. Both cases are similar to an electrical problem solved by C. H. Lees.[75] The fringe permeance is defined in the usual way as the excess of the total permeance over that computed between the parallel parts of the slot. The formula for computing the fringe of permeance from the experimental data is similar to those previously mentioned. The permeance as plotted in Fig. 35 is that for the whole slot, per centimeter of axial length. Various approximate formulae have been proposed[76], most of which are based upon assuming the lines across the slot to be straight. These formulas are compared with the correct formula in Fig. 36 for the tooth tip angle of 45 deg

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[74] *Eclairage Electrique*, Vol. 30, p. 437; Vol. 51, p. 12.

[75] *Phil. Mag., loc. cit.*

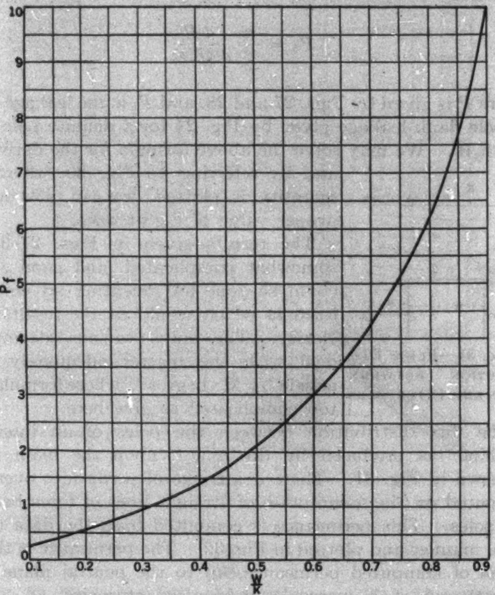

Fig. 32—Fringe of Leakage Permeance from Main to Interpoles

All of these formulas give null result when the pole tip angle is zero, and hence are in considerable error.

In Fig. 37 we have the field of flux produced by one armature coil embedded in nearly closed slots. At a distance $x = n\lambda$ from the first coil there is a second coil with a line of flux entering

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[76] E. Arnold, Wechselstromtechnik, Vol. 4, 1st Ed., p. 44. C. A. Adams, A. I. E. E. Trans., Vol. 24, (1905), p. 335. J. Rezelman, Lumiere Electrique, Vol. 10, (1910), p. 293.

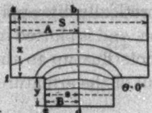
a
b
S
A
x
f
y
s
B
e
d
θ-0°

FIG. 33—DISTRIBUTION OF LEAKAGE FLUX IN SEMI-CLOSED SLOTS

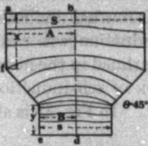
a
b
S
A
x
f
d
θ-45°
y
B
s
e
d

FIG. 34—DISTRIBUTION OF LEAKAGE FLUX IN SEMI-CLOSED SLOTS

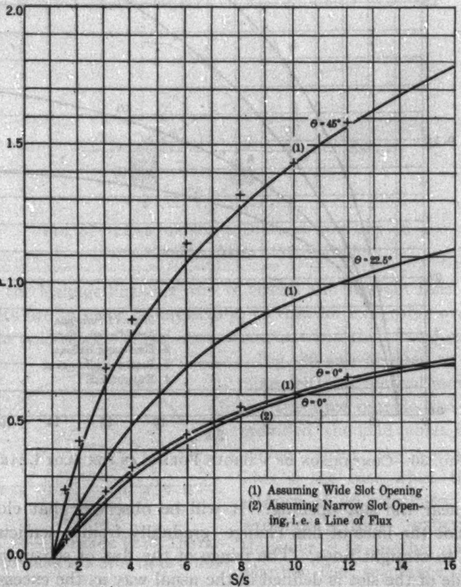

FIG. 35—PERMEANCE OF INTERNAL FRINGE OF SLOT LEAKAGE FLUX

the center of its slot. The flux inside this line links with only one coil, but that between this line and the center of the pole is flux of mutual induction. The permeance of this flux of mutual induction was evaluated theoretically by applying the method outlined in the historical section, and is plotted in Fig. 39.

The flux of self-induction is the whole flux up to the mouth of the slot. In Fig. 38 is shown a detail of the armature leakage flux near the slot opening. It will be observed that close to the slot the lines of flux change gradually from a semicircular form to straight lines. The fringe of the flux of self-induction outside of the slot is defined in the usual way as the excess over what would pass inside the slot opening, were the lines of force straight. The permeance of the flux was calculated and plotted in Fig. 39 against x, which is half of the slot opening, namely

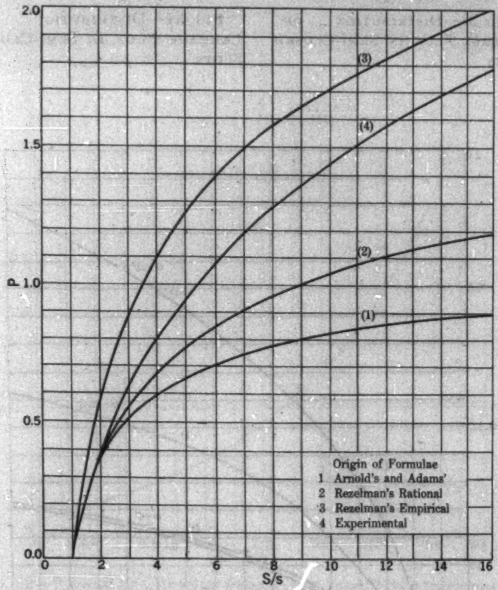

FIG. 36—COMPARISON OF VARIOUS FORMULAS FOR SLOT LEAKAGE

($s/2$). The result is correct only provided the slot width is small as compared to the pole pitch.

In Fig. 39 is also plotted Arnold's[77] formula for self- and mutual induction. This formula is based upon the assumption that the leakage lines are arcs of circles and straight lines. His results are in error theoretically, in that he integrates over the whole pole pitch. This error is corrected in the second edition.

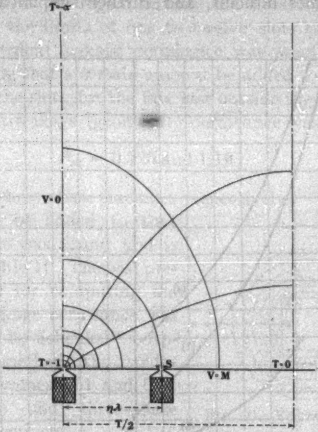

Fig. 37—Leakage Flux Distribution due to a Concentrated Armature Winding

Fig. 39 can be used to determine self and mutual induction for the flux outside the slots, provided the field poles are removed from the armature. This is the case when the reactance of an alternator is determined from experiment. However, it is another question whether the reactance so determined has much relation to that of the machine completely assembled. No correction should be made for the curvature of

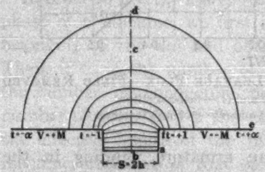

Fig. 38—Leakage Flux Distribution near the Mouth of a Slot

the armature surface, since a short theoretical investigation proved that it is not necessary. This is in contradiction to Arnold's and Rezelman's recommendation. When there are a number of slots per phase and per pole, the application of Fig. 39 becomes difficult, and further simplification becomes desirable.

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[77] Wechselstromtechnik, 1st Ed. Vol. 4, (1904), p. 44. See also Rezelman, Lumiere Electrique, Vol. 10, p. 259.

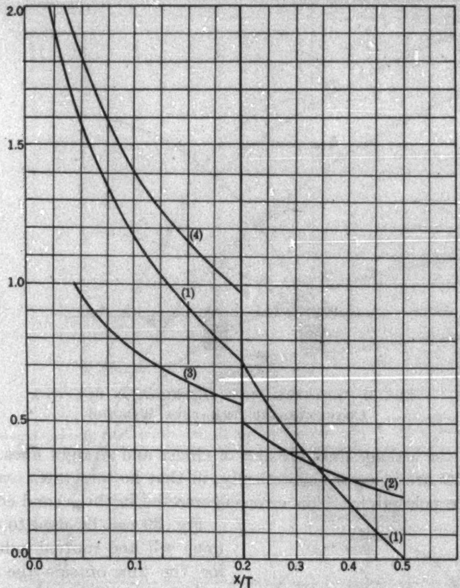

FIG. 39—PERMEANCE OF ARMATURE LEAKAGE FLUX—FIELD REMOVED

(1) and (2)—Mutual induction (3) and (4)—Self-induction
(1) and (4)—Exact formulas (2) and (3)—Arnold's formulas

The leakage flux set up by an armature winding in the region outside the slots, links in part with each slot individually, and in part with more than one slot. It is convenient, therefore, to calculate the inductance due to the leakage flux as if it linked with the whole of the group of conductors belonging to one phase under one pole. This inductance should include the effect of mutual induction between the phases. On the other hand, the leakage flux set up inside the slots is most conveniently calculated separately.

Using Fig. 39, and taking into account the factors mentioned, the writer worked out the equivalent leakage permeance of the flux set up in the region outside the slots. It was found that, between the limits of one to twelve slots per phase per pole, the equivalent leakage permeance was practically a constant; providing that a certain amount be added to the leakage permeance of the slots, for the flux just outside the slot opening. The equivalent leakage (geometric) permeance was found to be

$$P_{eq} = 0.725 \text{ and } 1.19 \tag{27}$$

for two- and three-phase machines respectively. The fringe of permeance to be added to that inside the slots was found and is recorded in Table II. The best previous method for computing the equivalent leakage permeance was that proposed by Schenkel[78]. Applying this method, the writer obtained the values 0.51 and 0.86 for two-phase and three-phase machines respectively.

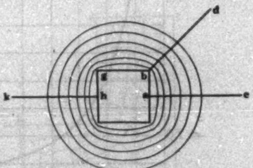

FIG. 40—EQUIPOTENTIAL SURFACES AROUND A SQUARE WIRE

TABLE II—VALUES OF EXTERNAL FRINGE OF SLOT LEAKAGE PERMEANCE.

(s/λ) =	0.60	0.50	0.40	0.30	0.20	0.15	0.10	0.05	0.025
ΔP_s =	−0.20	−0.10	−0.00	+0.10	+0.30	+0.40	+0.55	+0.85	+1.200

In order to use the above results to obtain the inductance per phase of a machine, we first add to the fringe of permeance belonging to the slot and obtain the total slot permeance P_s. Then, if C_s is the number of conductors per slot and C_{pp} are the number of conductors per pole, and per phase, P the number of poles, and S the number of slots per phase, and L the effective length of the machine; the inductance of the machine, exclusive of that of the end connections, is

$$L = (4\,\pi/10)\,(S\,C^2_s\,P_s\,L + P\,C_{pp}^2\,P_{eq}\,L)\,10^{-8} \tag{28}$$

The electrostatic equipotential surfaces around a square conductor are shown in Fig. 40. The capacity of a rectangular wire of dimensions a and b was investigated mathematically and found to be given by the following equation:

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[78] Electrotechnik und Maschinenbau, Vol. 6, (Feb. 1901), p. 54.

$$C = \frac{\pi \, K_a L}{L_n \, (KD/\text{perimeter})} \tag{29}$$

where C is the capacity between two wires D cm apart. K_a

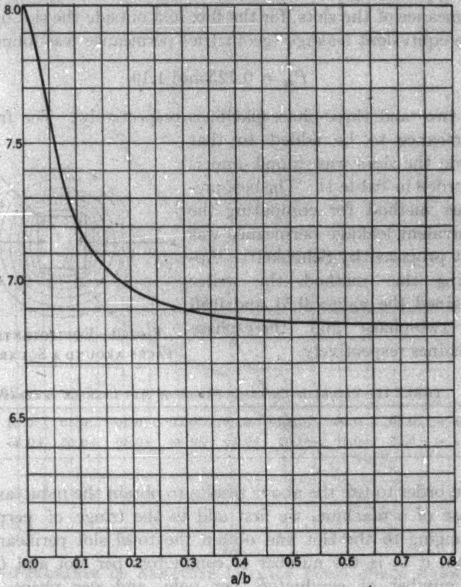

FIG. 41—FACTOR FOR DETERMINING CAPACITY OF RECTANGULAR WIRE

is the dielectric constant for air, L is the length of the wire in cm. and K is a factor plotted in Fig. 41, the perimeter of the wire being $2\,(a + b)$.

The above cases comprise all those of which the writer is prepared to report the permeance. However, the flux distribution in the cores of various machines was studied, also that in the air gap of alternators. Owing to saturation, the reluctance as measured by experiment in these cases would not be of great value; and for this reason it was not calculated. The reluctance of the air gap of alternators was omitted because the assumed shape of the pole is not used.

The flux distribution in the core of a transformer is shown in Figs. 42 and 43. While the flux lines could have been obtained by soldering electrodes to the broken lines *e f m n* and *g h k l*, this would have been awkward. By soldering electrodes to the edges *e g* and *l n* and passing current through the strip, the equipotential lines *f h* and *m k* were traced out. The L-shaped strip was then cut into three lengths *e f g h*, *f h k m*, and *k l m n*. The flux lines were then very easily obtained by soldering electrodes to the lines *g h*, *h k*, *k l*, *e f*, *f m*, and *m n*, and passing current through the three strips in the usual way. The writer is indebted to Mr. E. M. Shepard, Cornell '13, for the experimental work involved in this problem.

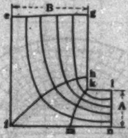

FIG. 42—FLUX DISTRIBUTION IN CORNER OF A TRANSFORMER

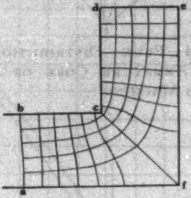

FIG. 43—FLUX DISTRIBUTION IN THE CORNER OF A TRANSFORMER

The flux within the core of an armature is shown in Fig. 44; this was suggested by test results published by Dr. Thornton.[79] The template has to be laid out with a calculated curve, the equation of which is obtained by the theory outlined earlier in the paper. This equation is

$$(x/R)\left[(x/R)^2 - 3(y/R)^2\right] = 1 \tag{30}$$

This figure was determined from experiments and compared with the curves published by Dr. Thornton and found to agree completely. This work was also performed by Mr. E. M. Shepard.

The flux distributions shown in Figs. 45, 46 and 47 were determined by calculation only, but the excellent agreement between experiment and theory in all other cases indicates that they should be reliable.

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[79] *I. E. E. Jour. Loc. cit.*

The theoretical shape of pole shoe required to give an absolutely sine wave of voltage in an alternator was calculated by the mathematical theory outlined in the Historical Section, for a two-pole alternator. The equation of this pole shoe was

$$(y/R) - [yR/(x^2 + y^2)] = 0.19 \qquad (31)$$

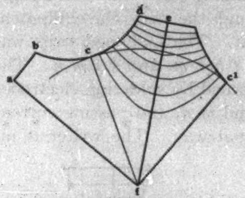

FIG. 44—FLUX DISTRIBUTION IN THE ARMATURE CORE OF A SIX-POLE MACHINE

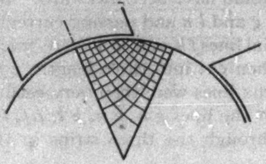

FIG. 45—FLUX DISTRIBUTION IN A FOUR-POLE ARMATURE WITH UNIFORM FLUX DENSITY IN THE AIR GAP

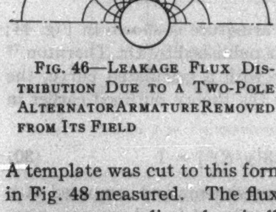

FIG. 46—LEAKAGE FLUX DISTRIBUTION DUE TO A TWO-POLE ALTERNATOR ARMATURE REMOVED FROM ITS FIELD

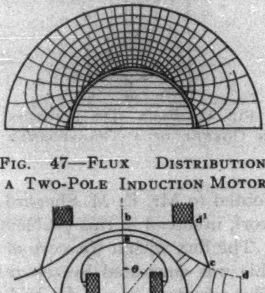

FIG. 47—FLUX DISTRIBUTION IN A TWO-POLE INDUCTION MOTOR

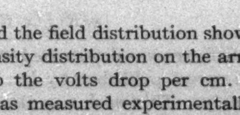

FIG. 48—POLE SHOES SHAPED TO GIVE SINE-WAVE E.M.F.

A template was cut to this form and the field distribution shown in Fig. 48 measured. The flux density distribution on the armature corresponding electrically to the volts drop per cm. of circumference of the circle, *c f*, was measured experimentally. This drop is plotted in Fig. 49. The experiment was repeated with a template shaped like *a b c d' e f* in Fig. 48 with the pole piece cut away in a convenient manner. This result also is plotted in Fig. 49. The first curve is an exact sine wave. The shape of the pole in a four-pole machine is similar to that in Fig. 48.

The mathematical theory is readily adapted to finding the correct pole shape for any shaped wave of flux desired. The application is not difficult, as the writer solved a particular case of this sort in a short time.

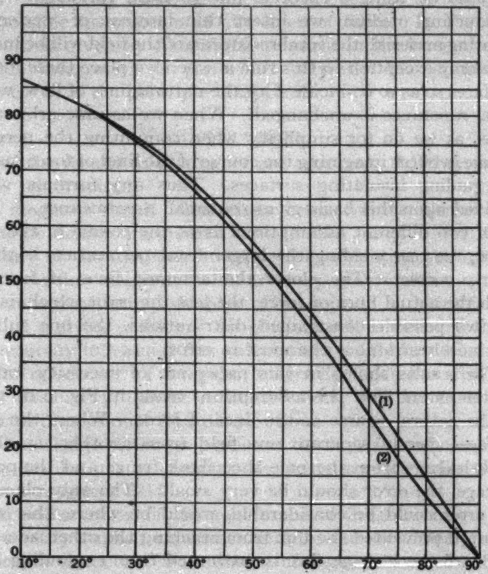

Fig. 49—Flux Density Distribution under Poles of Alternator

(1) Poles shaped for sine wave (2) Same pole tips cut away at convenient angle

It is believed that the most convenient way to use the results of this paper is by means of the curves shown. One no longer uses Frohlich's equation for saturation of iron, but the magnetization curve itself. It is more convenient to use curves of core loss than to calculate it from its coefficients. Likewise a set of curves like those in this paper for magnetic circuits of various forms, would facilitate magnetic calculations. (Those who prefer a formula, however, can use the equations for the curves which will be found in an appendix for reference.)

IV. Accuracy of Results

The accuracy of the assumptions made in the preceding two-dimensional magnetic fields, when used to compute the total reluctance of a dynamo, is the next topic to discuss. This we may do by using a theorem due to Lord Rayleigh.[80] If in a conducting medium we insert thin laminae of perfectly insulating material, the total resistance of the field will be increased. The only exception to this rule is when we place these insulating surfaces so as to co-incide with the natural lines of flow, when the total resistance is unchanged. When we assume arbitrary flux lines, as we do for simplicity when computing the permeance, we are in effect imagining the course of the lines of force restrained by guiding insulating surfaces. Thus any formula which is derived upon this basis gives too small a permeance.

Of two different assumptions as to the course of the lines of force, the one yielding the larger total permeance, is the most nearly correct. The closer the assumed lines of force agree with the actual lines of force, the less the error which is made. Of two possible constrained distributions, the one subject to the most restraint is the most in error.

The results shown in this paper are of necessity too small, by the extent that the assumptions made in Fig. 6 do violence to the natural course of the lines of force. Where the guiding surfaces merely separate one field from another, as the pole flank leakage from the pole shoe flank fringe and the pole shoe leakage, the error should be very small. The only place where the error could be considerable, would be where the surfaces assumed prevented the flux from reaching the other side. Thus in Fig. 6 the leakage flux is prevented from expanding beyond the pole yoke. Lord Rayleigh also gave a method for obtaining a superior limit to the permeance, but this was not applied by the writer.

It will be found, with three apparent exceptions, that the results shown in this paper are larger than those obtained by any of the approximations used hitherto. It may be concluded, therefore, that the results here given are closer to the truth. The three exceptions are Figs. 16, 36, and 39. In Fig. 16 the approximate curve given by Hawkins and Wrightman is based upon an assumption of the lines of force which encroaches upon the leakage field. Thus, although the permeance of the flux from the pole tip to the armature seems larger than it really is, the total permeance will be found to be less. In Fig. 36, curve No. 3, for a tooth tip angle of $\theta = 45$ deg., the approximation is larger than the curve here given. It is to be noted, however, that this is a purely empirical curve and does not correspond to any possible assumption of the lines of force. In Fig. 39 the formula as given by Arnold has an error in the integration. When this integration is performed correctly this apparent discrepancy with the principle disappears.

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[80] Theory of Sound, Vol. 2, Sect. 305, p. 175. See also V. Karpen, Comptes Rendus, Vol. 134, pp. 88-90.

V. CONCLUSIONS

Most of the results in this paper are apparent, but they may be briefly summarized.

(1) In magnetic circuit calculations a considerable portion of the magnetic field is irregular.

(2) Many of the methods in vogue for computing the reluctance of irregular magnetic fields are very inaccurate.

(3) Accuracy of an equal order of magnitude is desirable in all parts of a given problem. In particular it is believed that greater accuracy in leakage flux calculations would be desirable.

(4) The reluctance of irregular magnetic fields occurring in electrical machinery, can be estimated fairly well by studying various two-dimensional flux distributions.

(5) A knowledge of the properties of the functions of complex numbers, enables one to compute the reluctance of many two-dimensional magnetic fields.

(6) Particular cases of the reluctance of irregular magnetic fields are easily studied experimentally by the use of templates of the proper shape cut from sheets of high-resistance metal.

(7) The entire field around a dynamoelectric machine has been divided into sections, and the reluctance of each section determined to a greater degree of approximation than before. Many factors have been shown to have negligible effect, and in many cases present methods have been shown to be greatly in error.

(8) A number of other magnetic fields have been studied; in particular, the field around a square wire, the flux distribution in transformer cores, dynamo cores, and the air gap of alternators.

(9) It is of advantage to use graphical charts of permeance rather than empirical formulas.

(10) There are other cases of interest and value in the reluctance of irregular magnetic fields yet to be solved.

The writer wishes to acknowledge obligation to Cornell University in furnishing facilities for the experimental work, to Professors J. Macmahon, V. Karapetoff, and F. Bedell, and to Mr. F. W. Carter for suggestions, and to Mr. E. M. Shepard for valuable assistance with the experiments.

APPENDIX I.

MATHEMATICAL RESULTS

The fringe of tooth permeance for wide teeth and deep slots as shown in Fig. 9 is

$$P_f = \frac{2\pi}{\pi g} \cot^{-1} (S/2g) + \frac{2}{\pi} Ln\,[1 + (S/2g)^2] \qquad \textbf{(32)}$$

when the pole tip angle θ is 90 deg. The symbol *Ln* indicates the natural logarithm. When the pole tip angle is 0 deg.,

$$P_f = \frac{1}{\pi} Ln \frac{\sqrt{a} + 1}{\sqrt{a} - 1} + \frac{4}{\pi\,(\sqrt{a} + 1)} \qquad \textbf{(33)}$$

where the parameter a is determined from the equation

$$\frac{S}{2g} = \frac{1}{\pi} Ln \frac{\sqrt{a} + 1}{\sqrt{a} - 1} + \frac{2\sqrt{a}}{\pi\,(a-1)} \qquad \textbf{(34)}$$

When the pole tip angle θ is 45 deg.,

$$P_f = \frac{2}{\pi} Ln\,(4/a) + \frac{1}{\pi}\int_0^a \frac{\sqrt{1+t} - \left(1 - \frac{t}{a}\right)^{0.75}}{t\sqrt{t+1}}\,dt \qquad \textbf{(35)}$$

where the integration is performed graphically and a determined from the following equation:

$$\frac{\pi S}{2g} = \int_a^{+1} \frac{\left(1 + \frac{t}{a}\right)^{0.75}}{t\sqrt{1-t}}\,dt$$

$$+ \int_0^a \frac{\left(1 + \frac{t}{a}\right)^{\frac{3}{4}} \sqrt{1+t} - \left(1 - \frac{t}{a}\right)^{\frac{3}{4}} \sqrt{1-t}}{t\sqrt{1-t^2}}\,dt \qquad \textbf{(36)}$$

For infinitely narrow teeth, we have, with a pole tip angle of 90 deg.,

$$P_f = 2\,\frac{K\left(\operatorname{sech}\dfrac{\pi g}{s}\right)}{K\left(\tanh\dfrac{\pi g}{s}\right)} \tag{37}$$

where K is the complete elliptic integral of the first kind tabulated in Pierce's Tables of Integrals page 117. For large values of the air gap, and finite width of the teeth, the excess reluctance of the air gap plotted in Fig. 11 is

$$R_e = \frac{1}{\pi}\left(1 + \frac{S}{\lambda}\right) Ln\left(1 + \frac{S}{\lambda}\right) + \frac{1}{\pi}\left(1 - \frac{S}{\lambda}\right) Ln\left(1 - \frac{S}{\lambda}\right) \tag{38}$$

When the slots are shallow, and the teeth are infinitely narrow, the fringe permeance plotted in Fig. 10 is given by the equation

$$P_f = 2\,\frac{K\,(a)}{K\,(\sqrt{1-a^2})} \tag{39}$$

where a is a parameter which has to be determined, together with another parameter b, from the following equations:

$$\frac{s}{d+g} = \frac{K\,(b)}{K\,(\sqrt{1-b^2})} \tag{40}$$

$$\frac{d}{d+g} = \frac{F\left(\sqrt{1-b^2}, \sqrt{\dfrac{a^2-b^2}{a^2\,(1-b^2)}}\right)}{K\,(\sqrt{1-b^2})} \tag{41}$$

The permeance from the two pole tips of a machine to the armature, is less than that from tooth tips of the same shape by an amount

$$P_f = 2\,\frac{Ln\,(4)}{\pi} \tag{42}$$

Thus the permeance curves in Fig. 16 are similar in shape to those in Fig. 9, and can be plotted by applying the above correction P_f to equations (**32**), (**33**), and (**35**).

The permeance from the pole tips of a machine with projecting pole tips, as shown in Fig. 15 and plotted in Fig. 17, is given by the equation

$$P_f = \frac{1}{\pi} Ln \left(\frac{1+b^2}{4\,b^2}\right) + \frac{K}{2\pi g} \cos^{-1}\left(\frac{1-b^2}{1+b^2}\right) - \frac{L}{K}\frac{K}{g} \qquad \textbf{(43)}$$

where b is a root of the following equation:

$$\frac{L}{K} = \frac{1}{2\pi} \cos^{-1}\left(\frac{1-b^2+2b\,\frac{2g}{K}}{1+b^2}\right)$$

$$-\frac{2g}{\pi K} Ln \left\{\frac{2\sqrt{b\left(b-\frac{2g}{K}\right)\left(1+\frac{2\,bg}{K}\right)}+2b+(b^2-1)\frac{2g}{K}}{(1+b^2)\,(2g/K)}\right\} \qquad \textbf{(44)}$$

The permeance of the pole tip leakage fringe shown in Fig. 18 is given by

$$P_{lf} = \frac{2g}{\pi K}\cos^{-1}\left(\frac{b^2-1}{b^2+1}\right) - \frac{1}{\pi} Ln \frac{4}{1+b^2} \qquad \textbf{(45)}$$

the parameter b being the same as in the previous equation.

The leakage permeance from round poles to the neutral plane as plotted in Fig. 23, is given by the following equation:

$$P_l = \frac{\pi}{2}\left\{\frac{\cot^2\frac{\pi r}{2T}+\coth^2\frac{\pi r}{2T}}{\coth^2\frac{\pi r}{2T}\, Ln \cot\frac{\pi r}{2T} - \cot^2\frac{\pi r}{2T}\, Ln \coth\frac{\pi r}{2T}}\right\} \qquad \textbf{(46)}$$

The fringe of leakage permeance from both ends of long rectangular poles to the neutral plane between the poles of a multipolar machine as plotted in Fig. 24, is

$$P_f = \frac{4}{\pi}\left(\frac{T}{K}+1\right) Ln \left(\frac{T}{K}+1\right) + \frac{4}{\pi}\left(\frac{T}{K}-1\right) Ln \left(\frac{T}{K}-1\right) \qquad \textbf{(47)}$$

In machines of very short axial length, the same permeance, as plotted in Fig. 24, is

$$P_1 = 4\,\frac{K\left(\cos\dfrac{\pi K}{2T}\right)}{K\left(\sin\dfrac{\pi K}{2T}\right)}. \tag{48}$$

The total pole shoe flank permeance, to the armature end, which is plotted in Figs. 27 and 28 is

$$P = \frac{K\,(b)}{K\,\sqrt{1-b^2}} \tag{49}$$

where the two parameters b and c are determined from the equations following, when the armature projects beyond the field pole. Note that E is the elliptic integral of the second kind, found in Pierce's tables, pp. 117 and 119.

$$\frac{g}{f} = 1 - \frac{E\,(c,\,b)}{E\,(c,\,90^\circ)} \tag{50}$$

$$\frac{h}{f} = \frac{E\,(\sqrt{1-c^2}) - c^2\,K\,(\sqrt{1-c^2})}{E\,(c)} \tag{51}$$

When the field, however, projects beyond the armature, the parameters b and c are given by the following equations:

$$\frac{g}{h} = \frac{\displaystyle\int_0^{\cos^{-1} b} \sqrt{\sec^2\theta - c^2}\,\sec\theta\,d\theta}{\sqrt{c}\,\sqrt{1-c^2}\,E\,(\sqrt{1-c^2}) - \sqrt{c^5}\,\sqrt{1-c^2}\,K\,(\sqrt{1-c^2})} \tag{52}$$

$$\frac{f-g}{h} = \frac{(1/c)\;\;E\,(c) - (1-c^2)\;\;K\,(c)}{\sqrt{1-c^2}\;\;E\,(\sqrt{1-c^2}) - c^2\,\sqrt{1-c^2}\;\;K\,(\sqrt{1-c^2})} \tag{53}$$

The fringe of permeance from the main poles to the interpoles of a dynamo, which is plotted in Fig. 32, is

$$P_f = \frac{2}{\pi} Ln\left(\frac{1}{4}\right)\left(\frac{K}{K-W} - \frac{K-W}{K}\right) + \frac{2}{\pi}\left(\frac{K}{K-W} + \frac{K-W}{K}\right) Ln\left(\frac{2K}{W} - 1\right) \tag{54}$$

The permeance of the fringe of flux on the inside of an armature slot shown in Figs. 33, 34 and 35 is

$$P = \frac{1}{2\pi} Ln \frac{1}{4} \left(\frac{S}{s} - \frac{s}{S}\right) + \frac{1}{2\pi} \left(\frac{S}{s} + \frac{s}{S}\right) Ln \left(\frac{S+s}{S-s}\right) \qquad \textbf{(55)}$$

when the angle of the tooth tip is 0°; when the angle is θ, where θ is (π/n), we have the equation

$$P = \frac{1}{2\theta} Ln\,(S/s) + \frac{1}{\pi} \int_0^\infty \left\{ \sqrt[2n]{\frac{e^x - (S/s)^n}{e^x - 1}} \right.$$

$$\left. - \sqrt[2n]{\frac{e^x - 1}{e^x - (S/s)^n}} \right\}^2 dx \qquad \textbf{(56)}$$

The permeance of the armature leakage flux of mutual induction outside the slot is plotted in Fig. 39 and is given by the equation

$$P = \frac{2}{\pi} Ln \cot \frac{\pi x}{2T} \qquad \textbf{(57)}$$

where the distance $x = n\lambda$. The same formula will give the self-induction, provided we take $x = (S/2)$, and add to the permeance a constant C. The constant C has a value 0.241 as given by

$$C = \frac{1}{\pi} + \frac{Ln\ (\pi/4)}{\pi} \qquad \textbf{(58)}$$

The capacity between wires of rectangular cross-section is given by equation (**20**), where the constant K is given by

$$(K/8) = c\ \sqrt{1-c^2}\ E\ (\sqrt{1-c^2}) + E(c) - c^3\ \sqrt{1-c^2}\ K\ \sqrt{1-c^2}$$

$$- (1-c^2)\ K(c) \qquad \textbf{(59)}$$

The constant K and the elliptic function K are not to be confused.

The parameter c may be determined from equation (**53**) provided that we read (b/a) in place of $(f-g)/h$.

APPENDIX II

METHODS OF COMPUTING RELUCTANCE THEORETICALLY

The method of determining the reluctance of irregular magnetic fields mathematically is best understood by working out two typical cases. The two most representative cases are: the fringe permeance from the sides of infinitely narrow teeth, as plotted in Fig. 9, and the fringe of leakage permeance from rectangular poles, as plotted in Fig. 24.

If, in Fig. 7, we continue the sides of the teeth across the air gap, as is shown by the lines $n\ m$ and $o\ p$, these lines will be flux lines. We will convert this conductor by Schwartz's theorem into a half plane with straight line boundary, and then into a rectangle. The point n corresponds in the t plane to the point $t = -a$, m to the point $t = -1$, o to the point $t = +1$, and p to the point $t = +a$. If the slots are of infinite depth the point $t = \infty$ corresponds to the deepest part of the slot. In the W plane, the line $n\ m$ corresponds to the line $\phi = 0$, $m\ o$ to the line $V = 0$, $o\ p$ to the line $\phi = \phi_m$, and both nQ and Rp in part to the equipotential line $V = M$. By Schwartz's theorem we have

$$Z = \int C \frac{dt}{\sqrt{t^2-1}} \tag{60}$$

$$W = \int K \frac{dt}{\sqrt{(t^2-1)\ (t^2-a^2)}} \tag{61}$$

In equation (**60**) when t passes through infinity, there is a discontinuity of $jC\pi$ in the integral and a discontinuity in Z of the slot width S. This enables us to determine the constant C. Performing this substitution and integrating, equation (**60**), we obtain

$$Z = j\frac{S}{\pi}\, Ln\left(t+\sqrt{t^2-1}\right) = j\frac{S}{\pi}\cosh^{-1} t \tag{62}$$

When, in particular, $t = a$, we have that $Z = +jg$; whence by substitution

$$a = \cosh\left(\frac{\pi g}{s}\right). \tag{63}$$

The permeance is obtained directly from equation (**61**), for, by definition, the permeance is the ratio of ϕ_m to M; and these quantities are obtained by integrating equation (**61**) between the limits $t = -1$ and $t = +1$, and $t = +1$ and $t = +a$ respectively. Thus

$$P = \frac{\phi_m}{M} = \frac{2\int_0^1 dW}{\int_1^a dW} = 2\frac{K\ (1/a)}{K\ (\sqrt{1-(1/a)^2})} \tag{64}$$

By substituting the value for a in this last equation, the result given in Appendix I, equation (**37**) is obtained.

The leakage field shown in Fig. 21 can be adapted for mathematical treatment by drawing the line K–J prolonging the poles indefinitely in an axial direction. We will convert this case in a similar manner as the preceding, into first an infinite half plane, and then into a rectangle in the W plane. The point h corresponds to the point $t = -\infty$ in the t plane, c to the point $t = -a$, the point K to $t = -1$, J to the point $t = 0$, and f to $t = +\infty$. In the W plane the line h–C corresponds to the line $\phi = 0$, the line $C\ K\ J$ to the line $V = 0$, and the line J–f to the line $V = +M$. By Schwartz's theorem we have

$$Z = C\int\frac{\sqrt{t+1}\ dt}{t\ \sqrt{t+a}} \tag{65}$$

$$W = C_2\int\frac{dt}{t\sqrt{t+a}} \tag{66}$$

The constant C in equation (**65**) and the constant a can both be determined from the discontinuities in the integral when $t = 0$ and when $t = \infty$, in a manner similar to the preceding case. This transformation was given in a different problem by C. H. Lees.[81] The result is that the constant $C = -jT/2\pi$ and $a = (T/K)^2$. Also,

$$z = +j\frac{T}{2\pi}Ln\left\{\sqrt{t+1}\sqrt{t+(T/K)^2}+t+\frac{T^2+K^2}{2K^2}\right\}$$
$$-\frac{jK}{2\pi}Ln\left\{\frac{\sqrt{t+1}\ \sqrt{t+(T/K)^2}+(T/K)}{t}+\frac{T^2+K^2}{2TK}\right\} \tag{67}$$

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[81] *Phil. Mag.. loc. cit.*

If the flux passed directly between the pole $K\ J$ and the neutral plane, the permeance apparently in this region, say between the points $t = -1$ and $t = -e$, a small value, near zero, would be

$$P_{app} = \frac{2}{jK}\left[Z_{(t=-1)} - Z_{(t=-e)}\right]$$

$$= \frac{1}{\pi}\,Ln\left(\frac{4\,T^2}{(T^2-K^2)\;e}\right) - \frac{1}{\pi}\,Ln\left(\frac{T+K}{T-K}\right) \qquad \textbf{(68)}$$

On the other hand, the constant C_2 is determined from equation (**66**) by the fact that there is a discontinuity in the integral of the amount $jC_2\ \sqrt{(1/a)}$ when t passes through zero, and W changes suddenly by the amount jM. The permeance of the leakage flux can be determined from equation (**66**); namely, when t changes from $-a$ to $-e$, the flux passing is the definite integral of equation (**66**) taken between these limits. Hence by substitution and integration

$$P = \frac{\phi_m}{M} = \frac{1}{\pi}\,Ln\left(\frac{4\ (T/K)^2}{e}\right) \qquad \textbf{(69)}$$

The value of the fringe permeance is the excess of the total permeance over the apparent permeance. Combining equations (**68**) and (**69**) and multiplying the permeance by four, we get the final result, which is given in Appendix I, equation (**47**). The factor four is to give the fringe permeance from all four corners of the pole.

Discussion on "The Reluctance of Some Irregular Magnetic Fields" (Douglas), Deer Park, Md., June 29, 1915.

Charles R. Underhill: I wish to call attention to a special case of reluctance. It has to do with solenoid design; the design of plunger electromagnets, or magnets with movable cores.

Let it be assumed that a constant mean effective alternating e. m. f. at constant frequency is to be impressed upon a coil. When the constant mean effective alternating e. m. f. is impressed upon the coil, it is found that a certain mean effective current flows through the coil, and from this knowledge together with the number of turns and the dimensions of the coil, the permeance of the coil can be calculated, and since reluctance is the reciprocal of permeance it is a simple matter to determine the reluctance of the coil.

Now let it be assumed that there is a core or plunger at some distance from the coil. Upon moving the core or plunger endwise towards one end of the excited coil, it is noted that the mean effective current strength is decreased, showing that the inductance and, therefore, the permeance of the coil and core combination is increased. Looking at it another way, it may be said that the reluctance of the entire combination has decreased. Neglecting the eddy current and hysteresis losses, the total flux interlinked with the current in the coil is constant. The permeance of the coil (without the iron) is constant. Therefore the coil has a permeance of its own, and the core has a permeance of its own, which latter permeance changes with different intensities of magnetization in the core, and the total permeance is the sum of the coil permeance and the iron permeance.

The point is that in the design of plunger electromagnets it is impossible to use the customary equation $\mu = \mathfrak{B}/\mathfrak{H}$, but the intensity of magnetization $\mathfrak{I}$ in the iron and the magnetizing force $\mathfrak{H}$ in the coil must be separately treated, because the so-called solenoid effect or the leakage pull, due to a solenoid and plunger, is proportional to the product of the intensity of magnetization in the core and the magnetizing force in the coil, to use conventional terms. The maximum permeance is obtained when the middle of the core is at the middle of the coil.

I would emphasize the fact that there is at least one case where the total induction $\mathfrak{B}$ cannot be used as a whole, but must be separated into its two components, that is, the intensity of magnetization and the magnetizing force. This is the basis of Maxwell's fundamental equation for the mechanical force due to electromagnets, which I shall briefly describe.

The induction $\mathfrak{B} = 4\,\pi\,\mathfrak{I} + \mathfrak{H}$ gausses.

The mechanical pressure,

$$\frac{F}{S} = \frac{\mathfrak{B}^2}{8\,\pi} = \frac{(4\,\pi\,\mathfrak{I} + \mathfrak{H})^2}{8\,\pi} = 2\,\pi\,\mathfrak{I}^2 + \mathfrak{I}\,\mathfrak{H} + \frac{\mathfrak{H}^2}{8\,\pi}$$

dynes per sq. cm.

whence

$$F = S\left(2\,\pi\,\mathfrak{J}^2 + \mathfrak{J}\,\mathcal{H} + \frac{\mathcal{H}^2}{8\,\pi}\right) \text{ dynes.}$$

Therefore, it is seen that the mechanical force F is divided into three components, one of which is between the ends of the two half-cores: one between the two half-coils, and then there is a mechanical force acting between the ends of the half-cores and the half-coils. This mechanical force between the coils and the cores is the so-called "solenoid pull" which is exceedingly important in the design of plunger electromagnets with reasonably long air gaps or in cases where there is only one plunger acted upon by the current in the coil, and this mechanical force is $F = \mathfrak{J}\,\mathcal{H}$ dynes.

F. W. Peek, Jr.: Very complicated magnetic circuits often result in practical work; it is generally impossible to calculate these with any degree of accuracy, and sometimes even impossible to estimate the field distribution. An exactly similar but more difficult problem exists in the dielectric circuit. Improper flux distribution in the magnetic field means local loss; improper dielectric flux distribution in high-voltage insulation means loss and destruction of apparatus—a limit is imposed on voltage. Although it is difficult to calculate the dielectric and magnetic circuits, except in very simple forms, an analogy fortunately, exists between the electric, magnetic and dielectric circuits. Mr. Douglas has made use of this fact in his interesting work.

For the electric circuit Ohm's law states that the electric flux or current is equal to the e. m. f. divided by the resistance.

For the magnetic circuit a similar law states that the magnetic flux is equal to the m. m. f. divided by the magnetic resistance or reluctance.

Likewise for the dielectric circuit the dielectric flux is equal to the e. m. f. divided by the dielectric resistance. Thus Ohm's law for the three circuits becomes:

$$I = \frac{E}{R} \text{ electric circuit.}$$

$$\Phi = \frac{M}{R} \text{ magnetic current}$$

$$\Psi = \frac{E}{S} \text{ dielectric circuit.}$$

The shape of the magnetic lines of force may be approximately located by means of iron filings, or the dielectric lines of force by mica filings. Actual values necessary in design cannot, however, be obtained by this method. The values of the equipotential surfaces in the magnetic or the dielectric fields in space cannot be directly measured. On account of the analogy between the three circuits, certain lines in the one correspond to certain lines in the others. As electric currents are readily measured, the electric circuit may be made use of in determining the other two. For instance, if it is desired to determine the dielectric field between two electrodes, these electrodes may be placed in a proper electrolyte and the equipotential surfaces and lines of force of the electric circuit located by a galvanometer. These equipotential surfaces and lines of force correspond to the dielectric equipotential surfaces and lines of force which would exist if the electrodes were in a dielectric. The dielectric circuit may thus be very accurately plotted, so that the stresses at different points of the insulation may be predetermined and the insulation arranged in such a way in design to give maximum efficiency. The experimental determination becomes more difficult when insulations of several permittivities are used.

Messrs. Fortescue and Farnsworth have already described to the Institute, work that they have done along this line. More and more of this kind of work, especially in the dielectric circuit, must be done, otherwise a limit in the voltage at which apparatus may be operated will result.

Comfort A. Adams: Mr. Peek spoke of the magnetic circuit, the electric circuit and the dielectric circuit. There is an additional one, the thermal circuit.

John D. Ball: I think we all know how the fields and other magnetic circuits are now designed. We have a curve that represents the material more or less closely, and we add to that some constant, two per cent or much more, depending on the circuit and our previous experience with similar circuits. However, our methods in this respect are going to be much better, for two reasons. First, because of the fact that the testing methods are more accurate, and second, because the materials are manufactured with a greater degree of uniformity. The testing methods on magnetic materials have been discussed so many times that now we are in closer concordance than two years ago, and secondly, in the last six months we have secured a greater degree of uniformity in the manufacturing of magnetic materials than ever before. Two years ago I was interested in getting some data on the magnetic properties of materials, especially the magnetization curves. We found a variation between minimum and maximum samples of the same grade of steel on the order of 20 to 25 per cent, whereas in the case of materials manufactured in the last six months the variation is cut down to about one-quarter of that, showing that the manufacturers are producing more uniform materials. We can now get a much more economical design by saving our field copper and not putting so much energy in rheostats to compensate for variations and for mistakes. Therefore, a study of magnetic fields is right along with other work and gives us the advantage of still closer and more accurate design.

P. M. Lincoln: I do not see how the author can expect to recognize the phenomena of the magnetic saturation in reproducing the electrical circuit as he has.

Percy H. Thomas: He excluded that from his discussion.

L. W. Chubb: The hard part of the designing of magnetic circuits is the consideration of the reactions of the armature windings, local saturation, etc. As Mr. Lincoln suggests, the saturation in the pole horns and the pulsation of the flux caused by variable reluctance of the gap, due to the passage of the teeth, should be considered. In view of these very difficult problems we have found that it is best to work the pantagraph method or drawing board method of mapping fields, rather than to go through long mathematical calculations for a single machine. In the development of a new line of standard machines, the fields are more carefully worked out in a theoretical way, but experience has shown that the experimental and graphical methods are the most practical and serve as a check solution. In our use of the pantagraph method we have found it necessary to work with solid fields, because in tracing fields with plane models the end effect is not correctly included.

We had used the pantagraph method of tracing fields some years before it was used by Messrs. Farnsworth and Fortescue. In fact, the early magnetic work suggested their extension of the method.

The author's method of using conjugate flow to get direct flow lines is true only for plane figures, and the combination of two or more of these two-dimensional figures to obtain the solid field is, of course, most laborious and only an approximation.* The method which we use of submerging solid models in a conducting fluid gives the true equipotential surfaces and the flow lines or their projections can be readily worked out in any plane or surface.

F. W. Carter: In a communication to which Mr. Douglas makes reference, I dealt with the fringe flux at the edge of a rectangular pole where a pair of such poles are confronted with a smooth armature. Another method of treatment which occurred to me as perhaps a little nearer to the actual arrangement of a continuous current machine, is derived from the case of a pair of line poles, shown in Fig. 14 in the paper; the equipotential lines near to the line poles bear considerable likeness in the neighborhood of their tips to pole shoes, and the chief problem is that of identifying the most suitable of these. I have chosen the equipotential line which has the same extreme extension, in relation to the gap and the same radius of curvature at the extreme tip; the result of a particular case is shown in Fig. 1, which also shows the notation used. Fig. 2 gives the result in the form of working curves. Where interpoles are used, I usually measure c between exciting and interpole tips, thus assuming no drop of magnetic potential across the interpole face. It should be noted that my c is a half of Mr. Douglas's k and my σ applies to the fringe for one tip only and not a pair; accordingly both abscissa and ordinate of my Fig. 2 must be doubled to compare with Mr. Douglas's Figs. 16 and 17.

The fringe of flux at the end of a pole piece cannot be treated very satisfactorily, for the reason that the disposition of parts remote from the gap affects the results. If it is assumed that both the pole and the armature core extend to infinity, the total flux between them becomes logarithmically infinite. It accordingly becomes necessary to carry the integration only to a certain point, and it is debatable where the limit should be set. The result is indicated by the continued rise in the curves of Mr. Douglas's Fig. 27. Mr. Douglas's suggestion for the determination of the appropriate limit is of much interest.

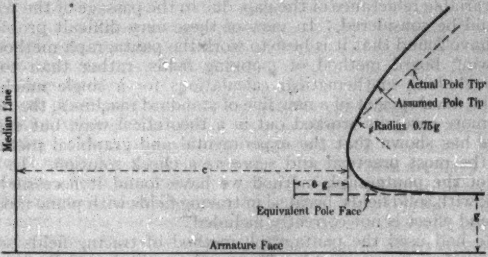
Actual Pole Tip
Assumed Pole Tip
Radius 0.75g
Median Line
c
σ g
Equivalent Pole Face
g
Armature Face

FIG. 1

The transformation involved, however, has its uses irrespective of this. One such application was made in a paper on "Magnetic Centering of Dynamo Electric Machinery", to which Mr. Douglas makes reference; here, however, only the change of flux due to end play is involved, and since the change all takes place in the neighborhood of the air gap, no difficulty arises although the difference of two infinities is involved. Another application of interest is that of finding the flux between two adjacent teeth separated by a slot carrying a conductor; the problem arises in connection with the determination of commutation constants in a machine without interpoles. For this purpose the integration may be carried to the center of the adjacent slot; Fig. 3 gives the result in the form of a curve, of which the ordinate is the fraction of the width of the slot that must be added to its depth in order to give the same total flux as between the adjacent teeth.

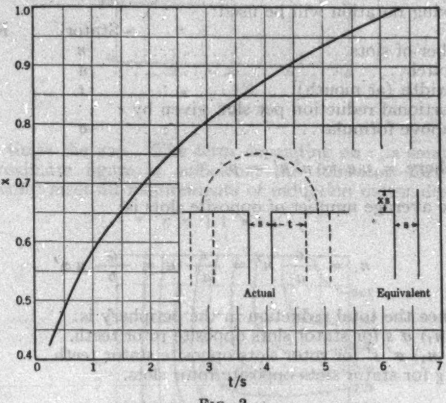

FIG. 3

The problem of the reluctance of a gap between surfaces both of which are slotted, as in the induction motor, is a fascinating one. In the article on "Air Gap Induction" published in the *Electrical World*, and referred to by Mr. Douglas, I showed that the effect of a slot opposite to a smooth face is as if the slot were absent, but the area of the face reduced by:

$$\sigma s = \frac{2}{\pi} \left\{ s \tan^{-1} \frac{s}{2g} - g \ln \left[1 + \left(\frac{s}{2g} \right)^2 \right] \right\}$$

where s is the width of the slot and g the gap. If two slots of widths s and s' are opposite one another, the appropriate reduction is:

$$\sigma_1 g = \frac{2}{\pi}\left\{\frac{s+s'}{2}\tan^{-1}\frac{s+s'}{2g} + \frac{s-s'}{2}\tan^{-1}\frac{s-s'}{2g}\right.$$

$$\left. - \frac{g}{2}\, ln \left[1+\left(\frac{s+s'}{2g}\right)^2\right]\left[1+\left(\frac{s-s'}{2g}\right)^2\right]\right\}$$

a formula which really includes the preceding as a particular case. The slots may be considered opposite as long as their centers are not more than $\frac{1}{2}c$ apart, where c is a linear quantity, of the order of the width of a slot, to be considered later. The following notation will be used:

	Stator	Rotor
Number of slots..........................	n	n'
Slot pitch...............................	a	a'
Slot width (at mouth)...................	s	s'
Proportional reduction per slot, given by above formula....................	σ	σ'

Periphery $= n\,a = n'\,a' = p$

The average number of opposite slots is:

$$n_1 = \frac{c}{a}\,n' = \frac{c}{a'}\,n = \frac{c}{p}\,n\,n'$$

Hence the total reduction in the periphery is:
$(n - n_1)\,\sigma\,s$ for stator slots opposite rotor teeth.
$(n' - n_1)\,\sigma'\,s'$ for rotor slots opposite stator teeth.
$n_1\,\sigma_1\,g$ for stator slots opposite rotor slots.

The resultant equivalent periphery is therefore:

$$p' = p - (n - n_1)\,\sigma\,s - (n' - n_1)\,\sigma'\,s' - n_1\,\sigma_1\,g$$

$$= p\left[1 - \frac{n\,\sigma\,s + n'\,\sigma'\,s'}{p} + \frac{\sigma\,s + \sigma'\,s' - \sigma_1\,g}{p}\,n_1\right]$$

$$= p\left[1 - \sigma\,\frac{s'}{a} - \sigma'\,\frac{s'}{a'} + \frac{(\sigma\,s + \sigma'\,s' - \sigma_1\,g)c}{a\,a'}\right]$$

The quantity within square brackets is the multiplier of the permeance or the reciprocal of the air-gap coefficient.

The curve of variation of flux between the opposite and remote positions of the slots was guessed at in the paper on magnetic centering; at considerable labor and with much cross-plotting I have now succeeded in computing it: with equal slots in the two members, the value of c is a little greater than the width of a slot, being 1.25 times with the slot twice the gap, 1.13 times with the slot three times the gap, and 1.07 times with the slot four times the gap. The term depending on c is small and an approximate figure is sufficient; the following formula will probably meet all requirements of induction motor design

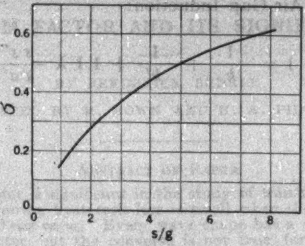

FIG. 4

$$c = 1.1\sqrt{s\,s'}$$

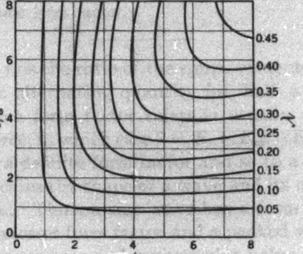

FIG. 5

The air gap coefficient K is accordingly given by:

$$\frac{1}{K} = 1 - \sigma\frac{s}{a} - \sigma'\,\frac{s'}{a'} + 1.1\cdot\lambda\,\frac{s\,s'}{a\,a'}$$

where $\lambda = \dfrac{\sigma\, s + \sigma'\, s' - \sigma_1\, g}{\sqrt{s\,s'}}$

Fig. 4 gives σ or σ', whilst Fig. 5 gives λ. It may be noted that $1 - \sigma \dfrac{s}{a}$ is the reciprocal of the air gap coefficient of a machine without rotor slots; if this is called k_1 and the corresponding quantity for a machine without stator slots, k', as in the article on Air Gap Induction:

$$\frac{1}{K} + 1 = \frac{1}{k} + \frac{1}{k'} + 1.1\,\lambda\,\frac{s\,s'}{a\,a'}$$

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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I—FORM FACTOR AND ITS SIGNIFICANCE

BY FREDERICK BEDELL

ASSISTED BY R. BOWN AND H. A. PIDGEON

ABSTRACT OF PAPER

Form factor is significant in the study of transformer losses; as is well known, hysteresis loss is small when the form factor is large, and *vice versa*. Every wave shape has a definite value of form factor; but the converse is not true, for a particular value of form factor does not indicate a particular wave shape. A wave may contain a third harmonic equal to seventy five per cent of the fundamental and still have the same form factor as a true sine wave. Form factor, therefore, has no general significance as an indicator of wave form or wave distortion.

A general expression for form factor is derived in terms of the relative amplitudes and phase positions of its harmonic components; curves are drawn showing the variation of form factor with the amplitude and phase of the third harmonic.

Various wave forms are shown, very unlike in appearance, having the same form factor.

FORM factor, f, is the ratio of the r.m.s. value to the average value of an alternating quantity for half a period. The quantity to which form factor refers is usually an alternating electromotive force, in which case $f = E \div E_{av}$. Each particular wave shape has a definite form factor and so to a certain extent form factor indicates the shape of a wave and its departure from a true sine wave. Thus, a sine wave has a form factor 1.1107; a flat wave has a lesser form factor and a peaked wave a greater. If the converse were true and a particular value of form factor indicated one particular wave shape, the form of a wave could be accurately defined in terms of form factor, but, as will be seen later, this is far from being the case.

It is true that, for certain purposes, the value of form factor is significant, as for example in the determination of transformer losses. Hysteresis loss in a transformer depends upon the maximum value of the magnetic flux. But, inasmuch as the flux ϕ is determined by the relation $\phi \propto \int e dt$, the maximum value of the flux is proportional to the average value of *e* and hence to the r.m.s. value divided by form factor; that is,

$$\phi_{max} = (E \div f) \times \text{constant}^1.$$

If a transformer is operated at a specified r.m.s. voltage from supply circuits having different voltage wave shapes, the maximum flux and hence the hysteresis loss will, accordingly, have different values for different form factors, becoming greater as the form factor becomes less, and *vice versa*. It is well known that a transformer operates less efficiently on a flat wave than on a peaked wave.

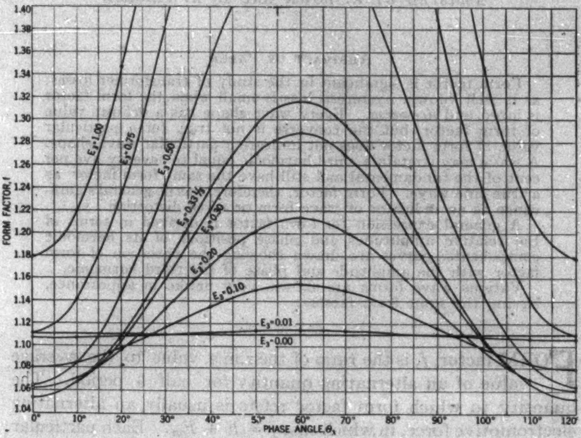

Fig. 1

If the r.m.s. voltage, *E*, is increased or decreased in direct proportion to form factor, so that the average voltage, *E*/*f*, remains constant, the hysteresis loss in the transformer remains unchanged and this fact is made use of in the determination of transformer losses on a sine-wave basis. For this purpose, the value of form factor can be ascertained by measuring the r.m.s

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[1] This constant is 10^8, when *E* is in volts. divided by 4 × frequency × cross section of iron in square centimeters × number of turns embracing it.

voltage by an ordinary voltmeter and the average voltage by means of a commutator[2] and d. c. voltmeter. To make simple the determination of hysteresis loss on a sine wave basis, without the necessity of determining the value of form factor, a special iron-loss voltmeter[3] has been devised by L.W. Chubb. An advantage in the use of this instrument is that it corrects for small variations in frequency as well as in wave form so as to give the loss for a standard frequency and sine wave form; a small error may be introduced, however, by the fact that eddy current loss and hysteresis loss do not follow the same law.

As has been shown, hysteresis loss depends in a very definite manner upon form factor which, accordingly, *in this connection* has a definite and useful significance. In general, however, form factor has no useful significance as an indication of the shape of a wave or its departure from a sine wave; in fact an irregular wave may have a third harmonic as large as 75 per cent of the fundamental and, if the harmonic is in the proper phase, as will be shown, still have the same form factor as a pure sine wave.

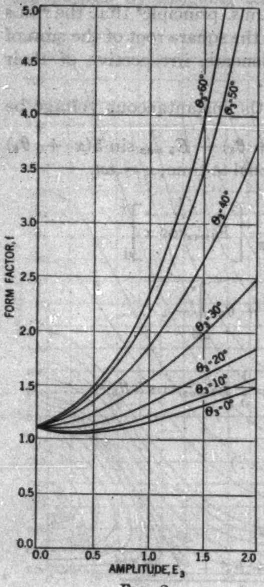

FIG. 2

An alternating wave is made up of a fundamental sine wave and harmonics with frequencies that are odd multiples of the fundamental frequency. The form factor of a complex wave depends not only upon the amplitude of these harmonics but upon their relative phase positions. The exact value of form factor is determined as follows:

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[2] See Lloyd and Fisher, "An Apparatus for Determining the Form of a Wave of Magnetic Flux," *Bulletin Bureau of Standards*, Vol. 4. p. 467, 1908; F. Bedell, The Use of the Synchronous Commutator in Alternating Current Measurements, *Journal Franklin Institute*, p. 385. Oct., 1913.

[3] Method of Testing Transformer Core Losses, Giving Sine-wave Results on a Commercial Circuit, A.I.E.E. TRANSACTIONS, Vol, 28, p. 417, 1909. See also pp. 432-473.

Let E_1, E_3, E_5, etc., be the r.m.s. values of the several harmonics. The r.m.s. value of the total voltage wave is

$$E = (E_1^2 + E_3^2 + E_5^2 + \ . \ \ . \ \ .)^{1/2}$$

This comes from the well-known r.m.s. principle[4] that the r.m.s value of any alternating quantity is the square root of the sum of the squares of its harmonic components, irrespective of their phase positions.

To find the average voltage, let the instantaneous voltage be

$e = E_{1max} \sin x + E_{3\ max} \sin 3(x + \theta_3) + E_{5\ max} \sin 5(x + \theta_5) + \ldots$, where x is a variable proportional to time; $x = \omega t$.

$$E_{av} = \frac{1}{\pi}\int_0^\pi e dx = -\frac{1}{\pi}\Big[E_{1max}\cos x\Big]_0^\pi$$

$$-\frac{1}{\pi}\Big[\frac{1}{3}E_{3max}\cos 3\ (x + \theta_3)\Big]_0^\pi - \ . \ \ . \ \ .$$

$$= \frac{2}{\pi}(E_{1max} + \frac{1}{3}E_{3max}\cos 3\theta_3 + \frac{1}{5}E_{5\ max}\cos 5\ \theta_5 + \ldots.),$$

$$= \frac{2\sqrt{2}}{\pi}(E_1 + \frac{1}{3}E_3\cos 3\theta_3 + \ldots.)$$

The form factor is, accordingly,

$$f = \frac{E}{E_{av}} = 1.1107\,\frac{(E_1^2 + E_3^2 + \ldots.)^{1/2}}{(E_1 + \frac{1}{3}E_3\cos 3\theta_3 + ..)}$$

In this equation E_1, E_3, etc., may represent either r.m.s. or maximum values.

In the following discussion the effect of the third harmonic only will be considered. Corresponding results for any other harmonic may be obtained in a like manner and will vary with the order of the harmonic; but in view of the results here shown and the fact that the results for any other harmonics would obviously be of the same character, such a laborious study does not seem worth while.

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[4] A proof of this principle is given on p. 391, "The Principles of the Transformer," 1896, by F. Bedell.

It is seen that form factor varies with the phase as well as with the amplitude of the third harmonic; that is, in the preceding equation there are three variables, E_3, θ_3 and f. Figs. 1, 2 and 3 are plotted by assigning constant values to each one of these three variables in turn and evaluating the equation so as to obtain the law of variation between the other two variables. Each figure will be discussed separately; it will be seen, however, that the remarks made in connection with any one figure apply to all.

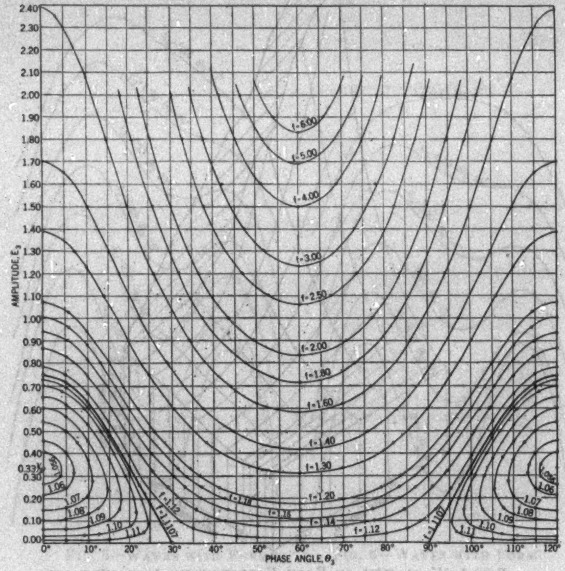

Fig. 3

In Fig. 1, each curve shows the variation of form factor with the phase angle θ_3 of the third harmonic when the harmonic has a definite value, namely, 0, 0.01, 0.10, 0.20, 0.30, 0.33, 0.50, 0.75 and 1.00 times the fundamental. The variation of θ_3 from 0° to 120° represents all possible values, for beyond these limits the curves repeat themselves.

When $E_3 = 0, f = 1.1107$ for all values of θ_3. When $E_3 > 0.75$, $f > 1.1107$ for all values of θ_3. When $E_3 < 0.75$ (the usual case), f may be greater or less than 1.1107, according to the value of θ_3.

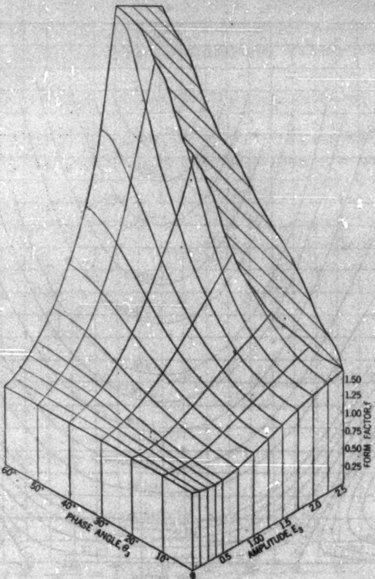

FIG. 4—VARIATION OF FORM FACTOR WITH AMPLITUDE AND PHASE OF THIRD HARMONIC

The maximum value of f occurs when $\theta_3 = 60$ deg. and this maximum is infinite[5] when $E_3 = 3.00$.

The minimum value of form factor occurs when $\theta_3 = 0$ deg. or 120 deg., and the lowest value of this minimum is 1.0537 when $E_3 = 0.33\frac{1}{3}$. The minimum value is 1.1107 when $E_3 = 0.75$, and is greater than 1.1107 when $E_3 > 0.75$.

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[5] When $E_3 > 3$, the value of f passes through infinity for two values of θ_3, one greater and one less than 60 deg.

Fig. 2 shows the variation of form factor with the amplitude of the third harmonic, when θ_3 is 0 deg., 10 deg., 20 deg., 30 deg., 40 deg., 50 deg. and 60 deg. As in Fig. 1, it is seen that, when $E_3 = 0$, $f = 1.1107$. When $E_3 < 0.75$, $f < 1.1107$ for small phase angles. The minimum value of f is 1.0537.

In Fig. 3, each curve is drawn for a constant form factor and shows the corresponding relation between E_3 and θ_3. The heavy curve is drawn for $f = 1.1107$, corresponding to a sine wave of electromotive force; E_3 may have any value between 0.75 (when $\theta_3 = 0$ deg. or 120 deg.) and zero. If either $E_3 > 0.75$ or $\theta_3 > 30$ deg., $f > 1.1107$. A form factor less than 1.1107 is obtained only when $E_3 < 0.75$ and $\theta_3 < 30$ deg. or $\theta_3 > 90$ deg.; for these cases there are two values of E_3 for each value of θ_3. The curves shrink to a single point when f has its minimum value, 1.0537, corresponding to $E_3 = .33\frac{1}{3}$ and $\theta_3 = 0$ deg. or 120 deg.

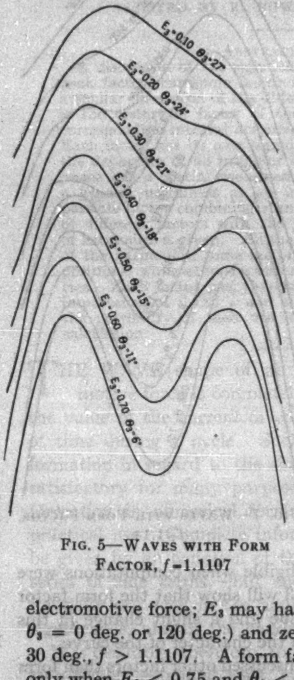

FIG. 5—WAVES WITH FORM FACTOR, $f = 1.1107$

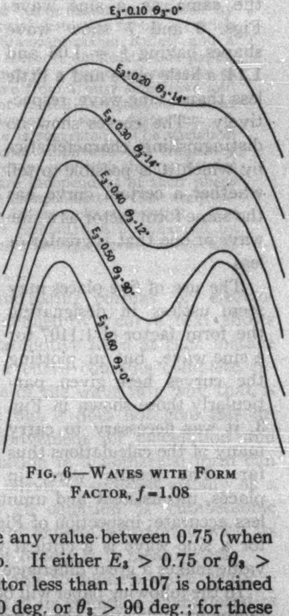

FIG. 6—WAVES WITH FORM FACTOR, $f = 1.08$

Fig. 4, drawn in isometric projection, shows the variation of form factor with both E_3 and θ_3. Cross-sections of Fig. 4, taken parallel to each pair of axes in turn, would give curves as shown in Figs. 1, 2 and 3.

To see whether or not there is any similarity of appearance in wave shapes that have the same form factor, Figs. 5, 6 and 7 were drawn by H. Papazian. The wave shapes in each figure have the same form factor, the corresponding values of E_3 and θ_3 being indicated in each case. Fig. 5 shows wave shapes having $f = 1.1107$, the same as a sine wave. Figs. 6 and 7 show wave shapes having $f = 1.08$ and 1.14, a little more and a little less than a sine wave, respectively. The curves show no distinguishing characteristics by which it is possible to tell whether a certain curve has the same form factor as a sine wave or one that is greater or less.

The use of five places may seem useless in designating the form factor of 1.1107 for a sine wave, but in plotting the curves here given, particularly those shown in Fig. 3, it was necessary to carry many of the calculations thus far. The results were, in places, inconsistent and unintelligible when computations were less accurate; inspection of Fig. 3 will show that the form factor for a sine wave is a critical value and a slight change in this value makes a great difference in the character of the curve.

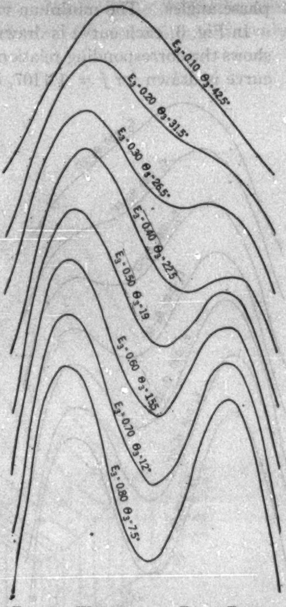

FIG. 7—WAVES WITH FORM FACTOR, $f = 1.14$

In the following paper will be discussed other factors than form factor for indicating the amount of distortion of a wave from a standard sine wave.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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II—DISTORTION FACTORS

BY FREDERICK BEDELL

ASSISTED BY R. BOWN AND C. L. SWISHER

ABSTRACT OF PAPER

A discussion of the significance and usefulness of deviation, peak factor, harmonic factor and curve factor, is followed by a similar discussion of the differential distortion factor δ (which is the distortion factor of the Standardization Rules) and a corresponding integral distortion factor σ defined in this paper. Each factor has its own significance as a numerical measure of the departure of an irregular wave from a pure sine wave and hence has a special usefulness for special purposes, as well as a general usefulness as an indicator of wave distortion. A possible factor combining δ and σ is suggested. The variation of different factors with the phase, amplitude and frequency of harmonics is given. All the factors vary with the amplitudes of the harmonics; some factors are independent of their phase positions, while other factors are independent of their frequencies. Each factor has, therefore, its own characteristics. The importance of δ and σ and their combination is enhanced by the possibility of their use in alternating-current theory and calculation.

THE WAVE shape of an alternating current or electromotive force is completely defined by a curve that shows the value of the current or electromotive force at each instant of time during a cycle. Such a curve contains complete information in regard to the shape of the wave in a way that is satisfactory for many purposes; but it does not give this information in numerical form, convenient for calculation and practical use. Complete information in a numerical form can be given by an equation of the curve,—expressed usually as a series of sine terms,—but such an equation is cumbersome for daily use even in the hands of experts acquainted with its significance, and in the hands of others it is meaningless.

It is desirable, therefore, to be able to define a wave shape—to a certain extent at least, even if its complete characteristics are not defined—by a factor, coefficient or percentage which will be convenient to use and readily understood. Such a factor commonly indicates the departure of the wave from some standard, and for a standard a sine wave is generally used.

The departure from a standard sine wave may be indicated in a way to be useful for general purposes only, as in case of *deviation*, or in a way to be useful for some specific purpose, as in case of *peak factor* (useful in testing of insulation) or of *form factor* (useful in connection with hysteresis loss but without general significance, as discussed in the preceding paper on form factor). These various factors for indicating the amount of wave distortion will be found to have varying degrees of usefulness both in theoretical investigation and in practical application. They are usually employed to indicate the distortion of voltage wave form, but may be used in a like manner to indicate the distortion of a current wave form when occasion arises.

The curve which is compared with the standard sine curve may be the curve of the actual wave itself or it may be the differential or integral of that curve,—as in the case of *differential distortion factor* and of *integral distortion factor* discussed later. Furthermore, for the standard sine curve of reference we may use the equivalent sine curve, as in the determination of *deviation*; or we may use the fundamental sine curve, as in the determination of *curve factor* and *harmonic factor*.

It is seen, therefore, that a variety of numerical factors are obtainable each with its own significance. It is the purpose of this paper to bring out certain characteristics of these several factors for comparison and to show the special significance of each, without attempting to give a detailed discussion of their determination or application. It is hoped that this may serve to open a discussion of the treatment of alternating currents of irregular wave shape, both in practise and in theory, by those particularly interested in such treatment. For greatest usefulness, a distortion factor should be definite and determinable, should be convenient as a general measure of wave distortion and should have such a significance that it can be used in making alternating current calculations.

DEVIATION

Deviation is determined by a direct comparison of the wave itself (rather than its differential or integral) with a sine wave of equal r.m.s. value. This sine wave is the equivalent sine wave and is so superposed for comparison that the maximum difference between it and the wave being studied is made as small as possible. Under these conditions, the maximum difference between corresponding ordinates, divided by the maximum value of the sine wave, is the *deviation*. To obtain deviation, the irregular curve and the equivalent sine curve may be plotted for comparison in rectangular or in polar coordinates, the latter having certain advantages for this purpose pointed out by L. W. Chubb (TRANSACTIONS, p. 838, Vol. XXXII.).

Although a direct comparison with a sine wave would seem to be the simplest possible measure of deviation, such a comparison in the manner described can only be made by a cut and try process and is not susceptible to simple mathematical analysis. Deviation has a certain obvious common sense meaning but, so far as we can ascertain, its value does not have a significance (such as is possessed by some of the factors discussed later) that can be used in calculation.

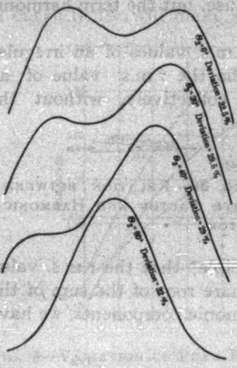

FIG. 1

Deviation indicates the departure from a sine curve in amount but not in kind. It gives no indication whether a wave is peaked or flat, regular or irregular, etc.; waves with the same deviation may have very different form factors, peak factors and differential and integral distortion factors.

Fig. 1 shows four wave shapes, very different in form, consisting of a fundamental and a third harmonic equal to 0.30 of the fundamental placed in various phase positions. The deviation is approximately 0.325 when the phase angle $\theta_3 = 0$; 0.295 when $\theta_3 = 20$ deg.; 0.29 when $\theta_3 = 40$ deg.; 0.32 when $\theta_3 = 60$ deg. It is seen that the deviation is not far from constant and that its value differs but little from the value of the harmonic, 0.30.

The deviation is measured in terms of the equivalent sine wave, while the harmonic is measured in terms of the fundamental sine wave, and these two sine waves are not coincident either in phase or amplitude. The ratio of their amplitudes is the curve factor, discussed later, but there is no simple relation between their phase positions. There is, accordingly, no relation between deviation and the amplitude of the harmonic or harmonics present that is simple and exact, although as in Fig. 1 the two may be nearly equal when only one harmonic is present.

Deviation is defined in the Standardization Rules of the Institute and although not in extensive use, it has an obvious practical significance.

CURVE FACTOR AND HARMONIC FACTOR

Curve factor is the ratio of the r.m.s. value of a wave to the r.m.s. value of the fundamental.

Harmonic factor is the ratio of the r.m.s. value of all the harmonics of a wave, exclusive of the fundamental, to the r.m.s. value of the fundamental.

The term curve factor has been in use, but the term harmonic factor we believe has not.

Let E and E_1 be the respective r.m.s. values of an irregular wave and its fundamental; let E_h be the r.m.s. value of all the component harmonics, taken collectively, without the fundamental. From the r.m.s. principle* that the r.m.s. value of an alternating quantity is the square root of the sum of the squares of the r.m.s. value of its harmonic components, we have the following relations:

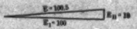

FIG. 2A—QUADRATURE RELATION BETWEEN FUNDAMENTAL, E_1, AND COLLECTIVE HARMONICS, E_h

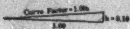

FIG. 2B—RELATION BETWEEN CURVE FACTOR AND HARMONIC FACTOR

$$E_h = (E_3{}^2 + E_5{}^2 + E_7{}^2 + \quad . \quad . \quad .)^{1/2}$$

$$E = (E_1{}^2 + E_h{}^2)^{1/2},$$

$$= \left(1 + \frac{E_h{}^2}{E_1{}^2}\right)^{1/2} \times E_1,$$

$$= (1 + h^2)^{1/2} \times E_1.$$

The harmonic factor h represents the combined harmonics in terms of the fundamental E_1, taken as unity. It is seen that h is independent of the phase and order of the several harmonics. One harmonic has the same weight as any other and it makes no difference whether many harmonics or only one are present.

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*For reference to proof, see the preceding paper on *Form Factor*.

$h \times 100$ is the value of the combined harmonics expressed as a percentage of the fundamental.

From the foregoing, we have

$$\text{Curve factor} = E/E_1 = (1 + h^2)^{1/2}$$

By a convenient approximation,

$$\text{Curve factor} = (1 + h^2)^{1/2} = 1 + (h^2 \div 2).$$

As an illustration, let $E_1 = 100$ and let the collective harmonics be 10% of the fundamental. The harmonic factor then is $h = 0.10$. The curve factor is 1.005 and the r.m.s. value of the total wave is 100.5, as shown in Figs. 2A and 2B. With h known, curve factor can be accurately calculated. The reverse calculation, however, is not so accurate, for a small error in curve factor will make a large error in h.

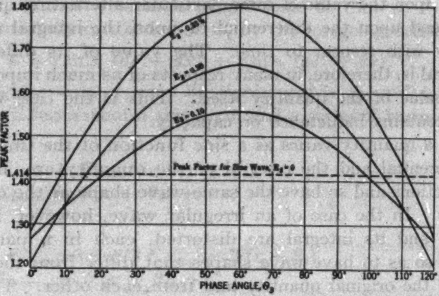

FIG. 3—VARIATION OF PEAK FACTOR WITH PHASE OF THIRD HARMONIC

Curve factor and harmonic factor are useful in their application but difficult in their determination. In an induction motor, the r.m.s. line voltage divided by curve factor gives the fundamental and this alone gives torque to the rotor.

PEAK FACTOR

Peak factor or *crest factor* is the ratio of the maximum to the r.m.s. value and is 1.414 for a sine wave. So far as the third harmonic is concerned, the peak factor will be a maximum when the phase angle $\theta_3 = 60°$ and a minimum when $\theta_3 = 0°$ or 120°, as shown in Fig. 3. The variation of θ_3 from 0° to 120° represents all possible values, for beyond these limits the curves shown in Fig. 3 repeat themselves. A simple expression for peak factor in terms of the amplitude and phase of the harmonic or harmonics present is, we believe, not obtainable. The curves in Fig. 3 were obtained by a partly analytical and partly graphical process.

Peak factor has an importance in various tests, particularly in insulation testing, and may be calculated from the measured r.m.s. and maximum values. One of the best methods for determining the maximum value of a voltage wave experimentally is to measure with a d-c. instrument and synchronous commutator the current taken by a condenser connected across the circuit to be tested.[1]

DIFFERENTIAL AND INTEGRAL DISTORTION FACTORS

In an alternating current circuit many effects do not depend directly upon the value of some particular alternating quantity but depend upon the differential or upon the integral of that quantity with respect to time. The value of its differential or integral is, therefore, in many respects of as much importance as the value of the quantity itself. This is the case when a circuit contains inductance or capacity.

When a quantity varies as a sine function of the time, both the differential and the integral of the quantity are likewise sine functions and so have the same wave shape as the original quantity. In the case of an irregular wave, however, its differential and its integral are distorted, each in a particular manner, so as to have wave shapes that differ from the wave shape of the original quantity and from each other. The distortion either of the differential wave or of the integral wave, compared with a sine wave as a standard, may, therefore, be taken as a measure of the distortion of the original wave itself. The two results will be different in their numerical values and in their significance and application.

Based on the foregoing are the following definitions:

The *differential distortion factor* (δ) of a wave is the ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

The *integral distortion factor* (σ) of a wave is the ratio of the r.m.s. value of the integral of the wave with respect to time to the r.m.s. value of the integral of the equivalent sine wave.

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[1] See Chubb and Fortescue, A. I. E. E. TRANSACTIONS, Vol. 32, 1913, p. 739; F. Bedell, *Electrical World*, Vol. 62, 1913, p. 378; F. Bedell, *Journal of the Franklin Institute*, Oct. 1913.

It will be seen that the factor δ is the distortion factor as now defined in the Standardization Rules of the Institute. The corresponding factor σ, based on the integral instead of the differential relation, will also, it is believed, be found useful, both in itself and in conjunction with δ. A following paper, by F. M. Mizushi, shows the application of these factors δ and σ and of $1/\delta\sigma = -\cos\Psi$ in obtaining certain solutions for non-harmonic alternating currents. These factors become more desirable as they are given a rational as well as an empirical basis. The significance of δ and σ is brought out in the subsequent paragraphs.

DIFFERENTIAL DISTORTION FACTOR

Let e be the instantaneous value of an irregular voltage wave and let e' be the instantaneous value of its equivalent sine wave. If x is a variable proportional to time ($x = \omega t$), the differential distortion factor is, by the foregoing definition,

$$\delta = \text{r.m.s.}\ (de \div dx) \div \text{r.m.s.}\ (de' \div dx).$$

The irregular wave, e, may be represented in the well-known manner by a fundamental sine term and a series of harmonics; thus,

$$e = E_{1max} \sin x + E_{3max} \sin 3(x + \theta_3) \\ + E_{5max} \sin 5(x + \theta_5) + \ldots$$

Hence,

$$de \div dx = E_{1max} \cos x + 3\, E_{3max} \cos 3\,(x + \theta_3) \\ + E_{5max}\ \cos 5\ (x + \theta_5) + \ldots.$$

By the r.m.s. principle already referred to, we have then

$$\text{r.m.s.}\ (de \div dx) = (E_1^2 + 9E_3^2 + 25\, E_5^2 + \ldots.)^{1/2},$$

where E_1, E_3, etc., are r.m.s. values.

For the equivalent sine wave, we have, in a like manner,

$$e' = E_{max} \sin (x + \alpha);$$
$$de' \div dx = E_{max} \cos (x + \alpha);$$
$$\text{r.m.s.}\ (de' \div dx) = E = (E_1^2 + E_3^2 + E_5^2 + \ \ldots)^{1/2}.$$

The differential distortion factor is, accordingly,

$$\delta = \frac{(E_1^2 + 9E_3^2 + 25E_5^2 + \ . \ \ . \ \ .)^{1/2}}{(E_1^2 + E^2_3 + E_5^2 + \ \ . \ \ . \ \ .)^{1/2}}$$

In this last equation E_1, E_3, E_5, may be either maximum or r.m.s. values.

It is seen that δ depends only upon the amplitude and the order or frequency of the several harmonic components, being independent of their relative phase positions. δ is unity for a sine wave and is greater than unity for an irregular wave by an amount that increases with the amplitude and order of the harmonics present. In the foregoing discussion, terms for odd harmonics only have been introduced; terms for even harmonics can be introduced in a like manner.

When only one harmonic is present, the variation of δ with the amplitude of the harmonic is shown by the curves in Fig. 4; each curve is drawn for a particular harmonic, the amplitude of which is expressed in terms of the fundamental which is taken as unity. The curves in Fig. 4 for the third, fifth, seventh and ninth harmonics approach the values 3, 5, 7 and 9, respectively, as their amplitudes approach infinity. The variation of δ with the order of the harmonic is shown in Fig. 5. Figs. 4 and 5 indicate that δ increases in a regular and more or less uniform manner with the frequency and amplitude of any single harmonic present. It is seen that more weight is given to an harmonic of high frequency than to an harmonic of low frequency; whether this is an advantage or otherwise will depend upon the point of view and upon the nature of the case under consideration.

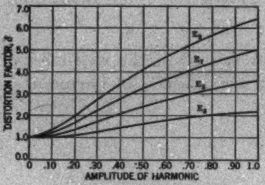

FIG. 4—VARIATION OF DISTORTION FACTOR δ, WITH AMPLITUDE OF HARMONIC

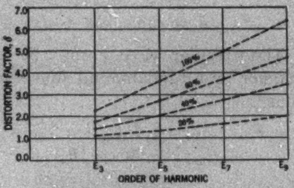

FIG. 5—VARIATION OF DISTORTION FACTOR δ, WITH ORDER OF HARMONIC

When more than one harmonic is present, the result is not so regular and is not so easy to interpret.

It may be shown that the current flowing into a condenser is directly proportional to δ; that is, $I = \delta\, C\omega E$. It is seen, therefore, that δ is directly proportional to the condenser admittance and inversely proportional to the condenser reactance. Experimental methods for determining δ are thus indicated, as well as definitions for δ in terms of condenser current, condenser admittance or condenser reactance. Thus, in terms of reactance,

$$\delta = \frac{1}{C\omega} \div \frac{E}{I};$$

which gives the definition:

The differential distortion factor δ of a distorted voltage wave is the ratio of the reactance $(1 \div C\omega)$ of a condenser on a sinusoidal voltage to its reactance (E/I) on the distorted voltage.

Suggestions as to the measurement of differential distortion factor and its definition will be found in a paper[2] by C. M. Davis and in its discussion.

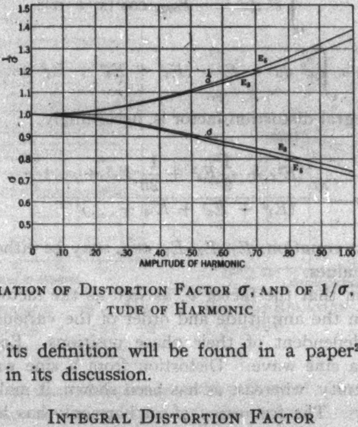

Fig. 6—Variation of Distortion Factor σ, and of 1/σ, with Amplitude of Harmonic

Integral Distortion Factor

According to the definition already given, the integral distortion factor has a value

$$\sigma = \text{r.m.s.} \int e\,dx \div \text{r.m.s.} \int e'\,dx,$$

where e and e' are the instantaneous values of an irregular wave and its equivalent sine wave, respectively, and x is proportional to time.

---

[2] "A Proposed Wave Shape Standard", Transactions, A. I. E. E., p. 775, Vol. XXXII, 1913; discussion, pp. 831-845.

Substituting for e a series of sine terms, as before, and integrating, we have

$$\int e dx = -E_{1max} \cos x - \frac{1}{3} E_{3max} \cos 3(x + \theta_3) + \ldots$$

and

$$\text{r.m.s.} \int e dx = \left(E_1^2 + \frac{1}{9} E_3^2 + \frac{1}{25} E_5^2 + \quad \ldots \right)^{1/2}.$$

We have, also, for the equivalent sine wave

$$e' = E_{max} \sin (x + \alpha);$$

$$\int e' \, dx = -E_{max} \cos (x + \alpha);$$

$$\text{r.m.s.} \int e' \, dx = E = (E_1^2 + E_3^2 + E_5^2 + \ldots)^{1/2}.$$

The integral distortion factor is, accordingly,

$$\sigma = \frac{\left(E^2_1 + \frac{1}{9} E_3^2 + \frac{1}{25} E_5^2 + \ldots\right)^{1/2}}{(E_1^2 + E_3^2 + E^2_5 + \ldots)^{1/2}}.$$

In this last equation, E_1, E_3, E_5, etc., may be either maximum or r.m.s. values.

It is seen that the factor σ, as well as the factor δ, depends solely upon the amplitude and order of the various harmonics, and is independent of their phase positions. Each factor is unity for a sine wave. Distortion from a sine wave makes σ less than unity, whereas, as has been shown, it makes δ greater than unity. The frequency of an harmonic has less effect on the value σ than on the value of δ.

In Fig. 6 is shown the variation of σ and $1/\sigma$ with the amplitude of the harmonic when the 3rd, or 5th harmonic alone is present. For any harmonic higher than the 5th, the values of σ and $1/\sigma$ are practically the same as for the 5th; thus, for an harmonic equal to 0.60, σ is 0.864 for the 5th, 0.861 for the 7th, 0.86 for the 9th harmonic. (This holds for harmonics of reasonable finite amplitudes, but not when the amplitudes approach infinity; σ then approaches 1/3, 1/5, 1/7 and 1/9 for the 3rd, 5th, 7th and 9th harmonics, respectively.)

Fig. 7 shows how little variation there is of σ and $1/\sigma$ with the order of the harmonic. It will be recalled that δ, on the other hand (see Fig. 5), varies practically in proportion to the order of the harmonic.

To see what relation there may be between σ and δ, curves are plotted in Fig. 8 showing the values of σ and $1/\sigma$ corresponding to different values of δ. It is seen that there is no simple relation connecting these quantities.

It can be shown that inductive reactance on a distorted voltage wave is inversely proportional to σ; that is,

$$I = \sigma E \div L\omega; \qquad \sigma = L\omega \div (E/I).$$

Hence the definition:

The integral distortion factor σ of a distorted voltage wave is the ratio of the inductive reactance ($L\omega$) of a coil on a sinusoidal voltage to its reactance on the distorted voltage. The reactance on the distorted wave for most purposes can be considered as being equal to E/I, for a small resistance included with the reactance would introduce but little error, on account of the fact that the effects of resistance and reactance are in quadrature. In precise measurements a correction for resistance might be applied.

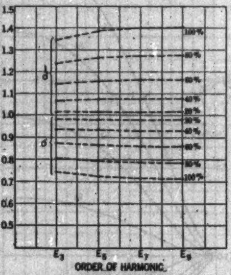

FIG. 7—VARIATION OF DISTORTION FACTOR σ, AND OF $1/\sigma$, WITH ORDER OF HARMONIC

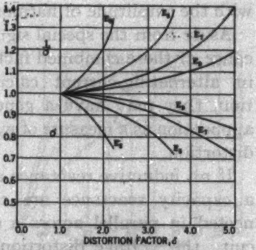

FIG. 8—RELATION BETWEEN σ, $1/\sigma$, AND δ.

COMBINED DISTORTION FACTOR

As there are certain merits in each of the distortion factors δ and σ, and also corresponding disadvantages, according to whether it is desirable to give more or less weight to the higher harmonics, a combined factor might be found—a useful compromise that would be free from the objections to either one alone. Furthermore, in alternating current calculation, as brought out in the following paper by Mr. Mizushi, certain results depend not upon the factor δ or the factor σ alone, but upon their product $\delta\sigma$, and upon $\Psi = -\cos^{-1}(1 \div \partial\sigma)$. Figs. 9, 10 and 11 are, accordingly, drawn to show the characteristics of these combined factors.

Fig. 9 shows the variation of $\delta\sigma$ and $1/\partial\sigma$ with the amplitude of harmonic.

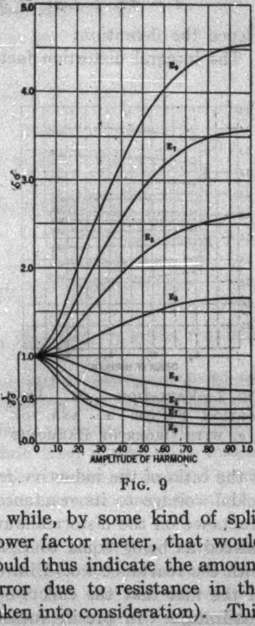

Fig. 9

Fig. 10 shows the systematic variation of $\delta\sigma$ with the order of the harmonic.

Fig. 11 shows the variation of the angle $\Psi = -\cos^{-1}(1 \div \delta\sigma)$ with the amplitude of harmonic.

Aside from the special significance of these combined factors in alternating-current calculation, they may have a general application as a measure of wave distortion.

If an inductive reactance and a capacity reactance are connected in parallel across a circuit, the voltage distortion of which is under consideration, $1 \div \delta\sigma$ is the cosine of the effective phase difference between the currents flowing in them. This suggests possibilities of measurement, should it be found worth while, by some kind of split dynamometer, phase meter or power factor meter, that would give the value of cos Ψ and would thus indicate the amount of wave distortion. (Possible error due to resistance in the inductance would have to be taken into consideration). This is a suggestion rather than a recommendation. Possibly some other combination of δ and σ than the one here suggested might prove practicable.

CONCLUSION

It is seen that there is a variety of factors, any one of which may be used as an indication of wave distortion. These factors, however, differ in their significance and give different weights to various elements or characteristics of wave distortion. Thus, peak factor and form factor (see the paper on form factor immediately preceding) are much affected by the phase relations of the component waves; deviation is less affected, while crest factor, harmonic factor, and the differential and integral distortion factors are not at all affected thereby.

Again, the differential distortion factor gives great weight to the order of an harmonic component, an harmonic of higher frequency having a much greater influence on the value of the factor than an harmonic of lower frequency and the same amplitude, while the integral distortion factor gives little weight to the order of an harmonic, and curve factor and harmonic factor give to it no weight at all.

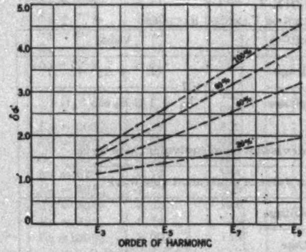

FIG. 10—VARIATION OF $\delta\sigma$ WITH ORDER OF HARMONIC

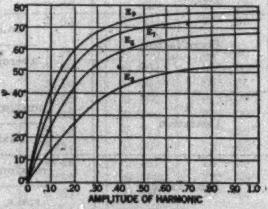

FIG. 11—VARIATION OF $\psi = \cos^{-1} 1/\delta\sigma$ WITH AMPLITUDE OF HARMONIC

Each factor, therefore, with its emphasis on particular characteristics, is suited for its own special use; thus, peak factor and form factor are useful for certain purposes already referred to, differential distortion factor and integral distortion factor are useful for theoretical calculations, etc.

As a general indicator of wave distortion, any one of several factors would be suitable—deviation, the curve and harmonic factors, the differential or integral distortion factor, or a combination of these two. Important elements in the selection of a factor are its *availability*, or the readiness with which it may be determined from the available data, experimental or otherwise, and the *definiteness* of its significance. The harmonic factor, or percentage of the combined harmonics, is very definite in its significance, for it states exactly the components of a wave that are present in addition to the fundamental sine wave and so gives directly the information that is desired for many purposes; but this factor seems hardly available for general use as there is no ready method for determining it. In this respect the distortion factors ∂ and σ or a combination of the two offer, it is believed, perhaps, the greatest possibilities for usefulness. Their value is enhanced by their specific usefulness in alternating current calculation.

APPENDIX I.

DEFINITIONS AND VALUES OF VARIOUS FACTORS

Factor	Definition	Value
Form factor, f.	$\frac{\text{r.m.s. voltage}}{\text{average voltage}}$	$1.1107\frac{(E_1^2+E_3^2+\dots)^{1/2}}{E_1+1/3\,E_3\cos 3\,\theta_3+\dots}$
Deviation	$\frac{\text{maximum deviation from equivalent sine wave}}{\text{maximum value of equivalent sine wave}}$	
Peak factor	$\frac{\text{maximum voltage}}{\text{r.m.s. voltage}}$	
Harmonic factor, h.	$\frac{\text{r.m.s. of harmonics}}{\text{r.m.s. of fundamental}}$	$\frac{(E_3^2+E_5^2+E_7^2+\dots)^{1/2}}{E_1}$
Curve factor $(1+h^2)^{1/2}$	$\frac{\text{r.m.s. voltage}}{\text{r.m.s. of fundamental}}$	$\frac{(E_1^2+E_3^2+E_5^2+E_7^2+\dots)^{1/2}}{E_1}$
Differential distortion factor, δ.	$\frac{\text{r.m.s. }(de \div dt)}{\text{r.m.s. }(de' \div dt)^*}$	$\frac{(E_1^2+(3E_3)^2+(5E_5)^2+\dots)^{1/2}}{(E_1^2+E_3^2+E_5^2+)^{1/2}}$
Integral distortion factor, σ.	$\frac{\text{r.m.s.}\int e\,dt}{\text{r.m.s.}\int e'\,dt}$	$\frac{E_1^2+(1/3E_3)^2+(1/5E_5)^2+\dots)^{1/2}}{E_1^2+E_3^2+E_5^2+\dots)^{1/}}$

***NOTE:** e' is instantaneous voltage of equivalent sine curve.

APPENDIX II.

NUMERICAL VALUES OF CERTAIN FACTORS

	δ	σ	$1/\sigma$	$\delta\sigma$	$1/\delta\sigma$	Ψ
$E_3 = 10\%$	1.04	0.996	1.004	1.036	0.971	13°—50′
$E_3 = 20\%$	1.14	0.983	1.017	1.12	0.894	26°—40′
$E_3 = 30\%$	1.29	0.963	1.038	1.24	0.806	36°—20′
$E_3 = 40\%$	1.45	0.937	1.067	1.36	0.736	42°—40′
$E_3 = 50\%$	1.61	0.907	1.102	1.46	0.685	46°—45′
$E_3 = 60\%$	1.76	0.875	1.143	1.54	0.650	49°—30′
$E_3 = 70\%$	1.91	0.841	1.189	1.60	0.625	51°—20′
$E_3 = 80\%$	2.03	0.808	1.238	1.64	0.610	52°—20′
$E_3 = 90\%$	2.14	0.775	1.290	1.66	0.602	53°—00′
$E_3 = 100\%$	2.23	0.745	1.342	1.66	0.602	53°—00′
$E_5 = 10\%$	1.11	0.995	1.005	1.104	0.907	24°—50′
$E_5 = 20\%$	1.39	0.981	1.019	1.363	0.730	43°—10′
$E_5 = 30\%$	1.73	0.960	1.041	1.66	0.602	53°—00′
$E_5 = 40\%$	2.08	0.932	1.073	1.94	0.516	59°—00′
$E_5 = 50\%$	2.41	0.900	1.111	2.17	0.461	62°—30′
$E_5 = 60\%$	2.71	0.864	1.157	2.34	0.428	64°—40′
$E_5 = 70\%$	2.98	0.828	1.208	2.46	0.407	66°—00′
$E_5 = 80\%$	3.22	0.791	1.264	2.54	0.394	66°—50′
$E_5 = 90\%$	3.42	0.755	1.324	2.58	0.388	67°—10′
$E_5 = 100\%$	3.61	0.722	1.385	2.61	0.384	67°—35′
$E_7 = 10\%$	1.21	0.995	1.005	1.20	0.833	33°—30′
$E_7 = 20\%$	1.69	0.981	1.019	1.66	0.602	53°—00′
$E_7 = 30\%$	2.23	0.959	1.043	2.14	0.463	62°—25′
$E_7 = 40\%$	2.76	0.930	1.075	2.56	0.390	67°—00′
$E_7 = 50\%$	3.26	0.897	1.115	2.93	0.342	70°—00′
$E_7 = 60\%$	3.70	0.861	1.161	3.18	0.314	71°—40′
$E_7 = 70\%$	4.10	0.823	1.215	3.37	0.297	72°—40′
$E_7 = 80\%$	4.43	0.786	1.272	3.48	0.287	73°—20′
$E_7 = 90\%$	4.74	0.749	1.335	3.55	0.282	73°—35′
$E_7 = 100\%$	5.00	0.714	1.400	3.57	0.280	73°—45′
$E_9 = 10\%$	1.34	0.995	1.005	1.33	0.752	41°—10′
$E_9 = 20\%$	2.02	0.981	1.019	1.98	0.505	59°—40′
$E_9 = 30\%$	2.76	0.959	1.043	2.65	0.378	67°—50′
$E_9 = 40\%$	3.47	0.930	1.075	3.22	0.310	72°—00′
$E_9 = 50\%$	4.12	0.896	1.116	3.69	0.271	74°—20′
$E_9 = 60\%$	4.70	0.860	1.163	4.04	0.248	75°—40′
$E_9 = 70\%$	5.22	0.820	1.219	4.28	0.234	76°—30′
$E_9 = 80\%$	5.68	0.784	1.275	4.45	0.225	77°—00′
$E_9 = 90\%$	6.06	0.746	1.340	4.52	0.221	77°—10′
$E_9 = 100\%$	6.40	0.712	1.404	4.55	0.220	77°—20′

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III—AN ANALYTICAL AND GRAPHICAL SOLUTION FOR NON-SINUSOIDAL ALTERNATING CURRENTS

BY F. M. MIZUSHI

Abstract of Paper

The solution which is usual in case of sinusoidal currents for series circuits containing *R*, *L* and *C* may be modified by the introduction of current distortion factors δ' and σ' so as to hold for non-sinusoidal currents. The usual solution for parallel circuits may likewise be modified by similar voltage distortion factors, δ and σ.

In Part I the general analytical solution for series circuits is followed by a corresponding graphical solution and a discussion of special cases. In Part II the general analytical solution for parallel circuits is likewise followed by a graphical solution and special cases. In both series and in parallel circuits, not only are the effects of *L* and of *C* changed in value by distortion, but these effects are changed, relatively, in phase and are no longer in exact phase opposition as in case of sinusoidal currents and voltages.

The mathematical transformations on which the solutions are based are given in an appendix.

FOR CIRCUITS containing constant resistance *R*, inductance *L* and capacity *C*, the general solution for sinusoidal alternating currents is well known and is in common use. It is desirable to have a corresponding general solution in simple form for non-sinusoidal alternating currents; to develop such a solution, both analytically and graphically is the object of this paper. Certain special cases, to which reference is given later, have been treated by A. Russell, but it is believed that no general solution has been published. The writer is indebted to Dr. F. Bedell, in whose class the investigation originated, for suggestion and assistance in the preparation of this paper, and to various members of the class for their cooperation. The same problem has previously been attacked in this laboratory by B. Arakawa[1], but in a somewhat different manner.

The treatment is divided into two parts, dealing with series and parallel circuits, respectively, and in each part the general analytical solution is followed by a graphical solution and a discussion of special cases.

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[1] Vector Representation of Non-Harmonic Alternating Currents, *Physical Review*, p. 409, Nov. 1909.

PART I. *R*, *L* AND *C* IN SERIES

Let the voltage and current at any instant be represented by

$$e = E_{1max} \sin(\omega t - \alpha_1) + E_{3max} \sin 3(\omega t - \alpha_3) + \ldots; \quad (1)$$

$$i = I_{1max} \sin(\omega t - \beta_1) + I_{3max} \sin 3(\omega t - \beta_3) + \ldots \quad (2)$$

The general relation between e and i for a circuit containing R, L and C in series, is shown by the well-known fundamental equation

$$e = Ri + L\frac{di}{dt} + \frac{1}{C}\int i dt \quad (3)$$

Let us square each side of this equation and multiply by the operator $\frac{1}{T}\int_0^T dt$. The left-hand side of the equation is then equal to the mean square voltage, for

$$\frac{1}{T}\int_0^T e^2 dt = E^2 \quad (4)$$

The right-hand side consists of six terms, as given in detail in Appendix I. After some reduction, two of these become zero and the remaining four may be written as follows:

$$E^2 = (RI)^2 + (\delta' L\omega I)^2 + \left(\frac{\sigma' I}{C\omega}\right)^2 - \frac{2L}{C} I^2 \quad (5)$$

or

$$E = \left(R^2 + (\delta' L\omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}\right)^{\frac{1}{2}} I = ZI \quad (6)$$

where Z is the impedance of the circuit, and δ' and σ' are, respectively, the differential and integral distortion factors for current, namely,

$$\delta' = \frac{(I_1^2 + (3\,I_3)^2 + (5\,I_5)^2 + \ldots)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots)^{\frac{1}{2}}} \tag{7}$$

$$\sigma' = \frac{\left(I_1^2 + \left(\frac{I_3}{3}\right)^2 + \left(\frac{I_5}{5}\right)^2 + \ldots\right)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots)^{\frac{1}{2}}} \tag{8}$$

δ' and σ' are *current* distortion factors, marked with a prime to distinguish them from the *voltage* distortion factors (δ and σ) used later. δ and δ' are *differential* distortion factors, while σ and σ' are *integral* distortion factors, the significance of which is discussed in the paper immediately preceding on Distortion Factors by F. Bedell.

Equation (6) gives the value of the impressed voltage at the terminals of a series circuit in terms of the current I and its distortion factors δ' and σ'. Inasmuch as the current has the same value in all parts of a series circuit, it is the current that is the connecting link between the various elements of such a circuit, and it is current distortion rather than voltage distortion that is significant in this case. On this account the solution for a series circuit is restricted in its application. For parallel circuits, the voltage is the common link between the several elements and, as will be shown later, the solution for parallel circuits is therefore in terms of voltage distortion, which is a form more suitable for practical applications.

For a non-sinusoidal current, $\delta' > 1$; $\sigma' < 1$.

For a sinusoidal current $\delta' = 1$, $\sigma' = 1$ and equation (6) reduces to the well-known form

$$E = I\sqrt{R^2 + \left(L\,\omega - \frac{1}{C\omega}\right)^2}.$$

The impedance of a series circuit becomes a minimum for a non-sinusoidal current when $\omega = \sqrt{\sigma' \div \delta'\,L\,C}$, or, for sinusoidal currents, when $\omega = \sqrt{\frac{1}{L\,C}}$

Graphical Solution; R, L and C in Series. Let us use for non-sinusoidal currents, the graphical relation in common use for sinusoidal currents, namely, that reactance and resistance may be represented by two sides of a right triangle the hypotenuse of which represents the impedance; as in Fig. 1. Thus,

$$Z = \sqrt{R^2 + X^2}$$

From equation (**6**) we also have

$$Z = \sqrt{R^2 + (\delta' L \omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}} \qquad (\mathbf{9})$$

whence

$$X = \sqrt{(\delta' L\omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}} \qquad (\mathbf{10})$$

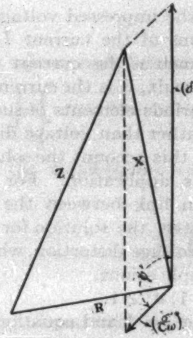

FIG. 1

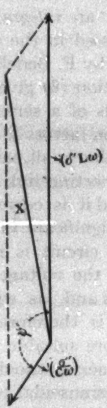

FIG. 2

When δ' and σ' are unity, (**10**) reduces to the well-known value for the reactance for sinusoidal currents, $X = L\omega - \frac{1}{C\omega}$; the total reactance is then the arithmetical difference of the inductive reactance and the capacity reactance, which are graphically represented in the same straight line but in opposite directions.

For a non-sinusoidal current, however, the inductive reactance $\delta' L\omega$ and capacity reactance $\frac{\sigma'}{C\omega}$ are no longer in a straight line, but are laid off as in Fig. 2 with an angle Ψ' between them, where

$$\cos \Psi' = -\frac{1}{\delta' \sigma'}$$

For non-sinusoidal currents, $\Psi' < 180$ deg., for sinusoidal currents, $\delta' = 1$, $\sigma' = 1$, $\Psi' = 180$ deg.

This graphical construction is justified as follows:

From Fig. 1 or Fig. 2, we have, by a well-known trigonometrical relation,

$$X = \sqrt{(\delta' L \omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 + 2(\delta' L \omega)\left(\frac{\sigma'}{C\omega}\right)\cos \Psi'}$$

Since $\cos \Psi' = -\frac{1}{\delta' \sigma'}$, this is identical with **(10)** already obtained analytically. $\delta' L \omega$, $\sigma'/C\omega$ and X are in one plane, at right angles to the resistance, R.

Special Cases for Series Circuit. For L and C, without resistance,

$$E = I \sqrt{(\delta' L \omega)^2 + \left(\frac{\sigma'}{C\omega}\right)^2 - \frac{2L}{C}} \qquad \textbf{(11)}$$

The reactance, as shown in Fig. 2, is the vector sum of $\delta' L \omega$ and $\frac{\sigma'}{C\omega}$, drawn with an angle Ψ' between them. With non-sinusoidal currents, capacity and inductance cannot fully neutralize each other so as to make the total reactance zero, as in the case of sinusoidal currents.

For R and L, alone,

$$E = I \sqrt{R^2 + (\delta' L \omega)^2} \qquad \textbf{(12)}$$

For R and C, alone,

$$E = I \sqrt{R^2 + \left(\frac{\sigma'}{C\omega}\right)^2} \qquad \textbf{(13)}$$

Figs. 3A and 3B show the reactance component, in quadrature to the resistance component, for these two cases. The solution for these two special cases has been given by A. Russell.[2]

For L alone,

$$E = \delta' L \omega I \tag{14}$$

For C alone,

$$E = \frac{\delta' I}{C\omega} \tag{15}$$

These equations indicate the possibility of determining the current distortion factors δ' and σ' experimentally by measuring the current and the voltage drop around a known inductance or capacity in series with the circuit in question.

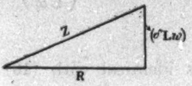

FIG. 3A

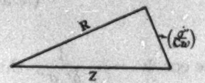

FIG. 3B

PART II. R, L AND C IN PARALLEL

Let the instantaneous values of voltage and current be represented by e and i, as already given in equations (**1**) and (**2**). The general relation between e and i for three circuits in parallel, one circuit containing a conductance $g = \frac{1}{R}$, another L and another C, is given by the general equation

$$i = ge + C\frac{de}{dt} + \frac{1}{L}\int e dt \tag{16}$$

This equation is of the same form as (**3**); it is to be noted however that e and i are interchanged, L and C are interchanged, and $\frac{1}{R}$ or g is written for R. By squaring and multiplying by the operator $\frac{1}{T}\int_0^T dt$, we obtain, in the same manner that equation (**5**) was obtained from equation (**3**), the following solution:

$$I^2 = (gE)^2 + \left(\frac{\sigma E}{L\omega}\right)^2 + (\delta C E \omega)^2 - 2\frac{C}{L}E^2 \tag{17}$$

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[2] See Alternating Currents, Vol. I, p. 80.

and

$$I = \left(g^2 + \left(\frac{\sigma}{L\omega}\right)^2 + (\delta\, C\omega)^2 - \frac{2\,C}{L} \right)^{\frac{1}{2}} E = Y E \qquad \textbf{(18)}$$

where Y is the admittance of the three circuits in parallel, and δ and σ are, respectively, the differential and integral distortion factors for voltage, as discussed in the preceding paper by Dr. Bedell.

$$\delta = \frac{(E_1^2 + (3E_3)^2 + (5E_5)^2 + \ldots)^{\frac{1}{2}}}{(E_1^2 + E_3^2 + E_5^2 + \ldots)^{\frac{1}{2}}} \qquad \textbf{(19)}$$

$$\sigma = \frac{\left(E_1^2 + \left(\frac{E_3}{3}\right)^2 + \left(\frac{E_5}{5}\right)^2 + \ldots\right)^{\frac{1}{2}}}{(E_1^2 + E_3^2 + E_5^2 + \ldots)^{\frac{1}{2}}} \qquad \textbf{(20)}$$

The admittance Y in equation (**18**) becomes a minimum when $\omega = \sqrt{\sigma \div \delta\, L\, C}$.

For a non-sine wave: $\delta > 1$, $\sigma < 1$. For a sine wave: $\delta = 1$, $\sigma = 1$, and equation (**18**) becomes

$$I = \left[g^2 + \left(\frac{1}{L\omega} - C\omega \right)^2 \right]^{\frac{1}{2}} \times E.$$

Graphical Solution; R, L, and C in Parallel. For a series circuit, use has been made above of the relation $Z = \sqrt{R^2 + X^2}$. For a parallel circuit, use may be made of the corresponding relation

$$Y = \sqrt{g^2 + b^2},$$

the admittance Y being made up of two quadrature components, namely, the conductance g, and the susceptance b, as shown in Fig. 4.

From equation (**18**) it is seen that

$$b = \sqrt{\left(\frac{\sigma}{L\omega}\right)^2 + (\delta\ C\omega)^2 - \frac{2\,C}{L}} \qquad \textbf{(21)}$$

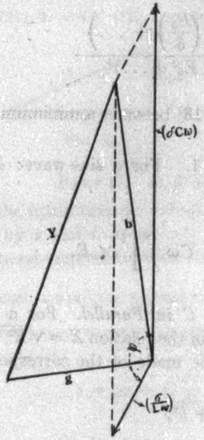
Figs. 4 and 5 show that the susceptance b is composed of the inductive susceptance $\left(\frac{\sigma}{L\omega}\right)$ and the capacity susceptance

$\delta C\omega$, laid off not in the same straight line (as for sinusoidal currents) but with an angle Ψ between them, where

$$\cos \Psi = -\frac{1}{\sigma\,\delta}. \tag{22}$$

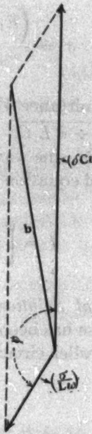
This construction is justified by the fact that, in Figs. 4 and 5,

$$b = \sqrt{\left(\frac{\sigma}{L\omega}\right)^2 + (\delta\, C\omega)^2 + 2\left(\frac{\sigma}{L\omega}\right)(\delta C\omega)\cos\Psi}$$



$(\delta C\omega)$
Y
b
Ψ
g
$\left(\frac{\sigma}{L\omega}\right)$

Fig. 4



$(\delta C\omega)$
b
Ψ
$\left(\frac{\sigma}{L\omega}\right)$

Fig. 5

which becomes identical with (21) upon the substitution of $-\frac{1}{\sigma\,\delta}$ for $\cos \Psi$.

Special Cases for Parallel Circuits. For L and C in parallel, without resistance,

$$I = \sqrt{\left(\frac{\sigma}{L\omega}\right)^2 + (\delta\, C\omega)^2 - \frac{2C}{L}} \tag{23}$$

The susceptance diagram for this case is shown in Fig. 5. Ψ is the phase difference between the currents in the inductance and capacity and its value indicates the amount of voltage distortion; for a sine wave of voltage, $\Psi = 180°$. This case is partially treated by A. Russell, Vol. I, p. 84.

For R and L, alone, in parallel

$$I = E\sqrt{g^2 + \left(\frac{\sigma}{L\omega}\right)^2} \tag{24}$$

For R and C, alone, in parallel

$$I = E\sqrt{g^2 + (\delta C\omega)^2} \tag{25}$$

The currents through the resistance and reactance, in these two cases, are in quadrature.

For L, alone,

$$I = \frac{\sigma E}{L\omega}\ ;\ \text{or}\ \sigma = L\omega I \div E \tag{26}$$

For C, alone,

$$I = \delta C E\omega\ ;\ \text{or}\ \delta = I \div C E \omega \tag{27}$$

The voltage distortion factors, δ and σ, may thus be determined experimentally by measuring the current taken by a pure inductive reactance or capacity reactance, respectively, when the voltage E is applied to its terminals.

APPENDIX I. DERIVATION OF EQUATION (5).

From equation (2) we obtain

$$\frac{di}{dt} = \omega I_{1max}\cos(\omega t - \beta_1) + 3\,\omega I_{3max}\cos 3(\omega t - \beta_3) + \ldots$$

$$\int i dt = -\frac{I_{1max}}{\omega}\cos(\omega t - \beta_1) - \frac{I_{3max}}{3\omega}\cos 3(\omega t - \beta_3)\ \ldots\ldots$$

Squaring (3), operating on it by $\frac{1}{T}\int_0^T dt$, and substituting these values for $\frac{di}{dt}$ and $\int idt$, we have for the right-hand side of the equation the following six terms, designated as (a), (b), (c), (d), (e) and (f). Two of these equal zero; the remaining four, after being reduced and simplified as below, appear in equation (5).

(a) $R^2 \frac{1}{T}\int_0^T i^2\,dt = R^2 I^2$, where I is the r.m.s. value of current.

$$\text{(b)}\quad L^2 \frac{1}{T}\int_0^T \left(\frac{di}{dt}\right)^2 dt = L^2\omega^2 \frac{1}{T}\int_0^T [\,I_{1max}\cos\;(\omega t - \beta_1]^2\,dt$$

$$+\,L^2\,\omega^2\,3^2\frac{1}{T}\int_0^T [\,I_{3max}\cos 3\;(\omega t - \beta_3)\,]^2\,dt + \ldots$$

$$= L^2\omega^2\;[\,I_1^2 + (3\,I_3)^2 + (5\,I_5)^2 + \ldots]$$

$$= (\delta'\,L\omega\,I)^2.$$

δ' is the differential distortion factor for current,

$$\delta' = \frac{(I_1^2 + (3\,I_3)^2 + (5\,I_5)^2 + \ldots)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots)^{\frac{1}{2}}}$$

It is to be noted that $\left(\frac{di}{dt}\right)^2$ involves the products of different frequencies, such as $\cos\;(\omega t - \beta_1)\cos 3\;(\omega t - \beta_3)$, etc., which become zero after being operated on by $\frac{1}{T}\int_0^T dt$.

$$\text{(c)}\quad \frac{1}{C^2}\frac{1}{T}\int_0^T (\textstyle\int idt)^2\,dt = \frac{1}{(C\omega)^2}\frac{1}{T}\int_0^T [\,-\,I_{1max}\cos\;(\omega t - \beta_1)\,]^2\,dt$$

$$+\,\frac{1}{(3C\omega)^2}\frac{1}{T}\int_0^T [\,-\,I_{3max}\cos 3\;(\omega t - \beta_3)\,]^2\,dt + \ldots$$

$$= \frac{1}{C^2\omega^2}\left[I_1^2 + \left(\frac{I_3}{3}\right)^2 + \left(\frac{I_5}{5}\right)^2 + \ldots\right]$$

$$= \left(\frac{\sigma' I}{C\omega}\right)^2$$

σ' is the integral distortion factor for current,

$$\sigma' = \frac{\left(I_1^2 + \left(\frac{I_3}{3}\right)^2 + \left(\frac{I_5}{5}\right)^2 + \ldots\ldots\right)^{\frac{1}{2}}}{(I_1^2 + I_3^2 + I_5^2 + \ldots\ldots)^{\frac{1}{2}}}$$

It is to be noted that $(\int idt)^2$, in the same manner as $\left(\frac{di}{dt}\right)^2$, has products of different frequencies, which become zero after being operated on by $\frac{1}{T}\int_0^T dt$.

$$\text{(d)} \quad 2\,RL\,\frac{1}{T}\int_0^T \left(\frac{idi}{dt}\right) dt$$

$$= 2\,R\,L\,I_{1\,max}^2\,\omega\,\frac{1}{T}\int_0^T \sin\,(\omega t - \beta_1)\,\cos\,(\omega t - \beta_1) dt$$

$$+ 6\,R\,L\omega I_{3\,max}^2\,\frac{1}{T}\int_0^T \sin 3\,(\omega t - \beta_3)\cos 3\,(\omega t - \beta_3)\,dt + \ldots$$

$$= 0$$

$$\text{(e)} \quad \frac{2R}{C}\,\frac{1}{T}\int_0^T (i \int idt)\,dt$$

$$= -\frac{2\,R\,I_{1\,max}^2}{C\omega}\,\frac{1}{T}\int_0^T \sin\,(\omega t - \beta_1)\cos\,(\omega t - \beta_1)\,dt$$

$$- \frac{2\,RI_3^2}{3C\omega}\,\frac{1}{T}\int \sin 3\,(\omega t - \beta_3)\cos 3\,(\omega t - \beta_3)\,dt - \ldots$$

$$= 0$$

(f) $$2\frac{1}{T}\int_0^T \left[\left(L\frac{di}{dt}\right)\left(\frac{\int idt}{C}\right)\right]dt$$

$$= -\frac{2L}{C}\,\frac{1}{T}\int_0^T [I_{1max}(\cos\omega t - \beta_1)]^2\,dt$$

$$-\frac{2L}{C}\,\frac{1}{T}\int_0^T [I_{3max}\cos 3\,(\omega t - \beta_3)]^2\,dt - \ldots.$$

$$= -\frac{2L}{C}(I_1^2 + I_3^2 + I_5^2 + \ldots.) = -\frac{2L}{C}\,I^2$$

DISCUSSION ON "FORM FACTOR AND ITS SIGNIFICANCE" (BEDELL, BOWN, PIDGEON), "DISTORTION FACTORS" (BEDELL, BOWN, SWISHER), AND "AN ANALYTICAL AND GRAPHICAL SOLUTION FOR NON-SINUSOIDAL ALTERNATING CURRENTS" (MIZUSHI), DEER PARK, MD., JUNE 29, 1915.

Joint Committee on Inductive Interference (communicated): Apropos of the present general consideration of irregular waveforms, this committee desires to call attention to an important aspect of this subject which has not hitherto received the attention which it merits. The interest of this committee in this matter arises from its bearing upon the subject of the committee's investigation—inductive interference. It is not overstating the facts to say that were it not for the irregularities of waveform of common occurrence in power circuits, the necessity for the formation of a committee of this character would not in all probability have as yet arisen. There is a strong presumption that the difficulties not arising from irregularities of wave form could have been overcome without the medium of such a committee.

It was forced to the attention of the committee at the outset of its investigation that practically the entire trouble arising from the inductive effect, upon telephone circuits, of power circuits in normal operation, is due to the harmonics present in the current and voltage waves of the power systems. The following extract is taken from the committee's report to the California State Railroad Commission, published in the PROCEEDINGS, Sept. 1914. (A. I. E. E. TRANSACTIONS, XXXIII, 1914, p. 1459).

"The frequency of the voice currents flowing in a telephone circuit ranges from about 200 cycles per sec. up to possibly 2000 cycles per sec. The average voice frequency is considered to be approximately 800 cycles per sec., and at about this frequency the telephone receiver is most sensitive. It is on account of these considerations that extraneous currents of the higher frequencies, arising from the harmonics of a power system, are relatively more detrimental to telephone service. The harmonics of the power systems have been found to be responsible for the greater portion of the inductive interference to telephone service, under normal operating conditions of parallel power circuits. Any extraneous current of a frequency within the audible range produces a disturbance which impairs the efficiency of a telephone circuit. The combined effects of all extraneous currents present, of frequencies within the range of audition, constitute the humming noise heard in the receiver of a telephone circuit which is subject to induction."

The report then goes on to state that the effect of the fundamental frequency (60 cycles or less) on telephone circuits is relatively unimportant unless the induction at such frequency is so severe as to constitute a physical hazard or to operate the protective devices on the circuits or interfere with superimposed telegraph service.

The report further sums up the matter in regard to irregular wave-forms as follows:

" The fact that practically all inductive interference to telephone circuits is due to the harmonic currents and voltages, renders it important that an effort be made to obtain rotating machinery for use in power systems which produces as nearly as is reasonably possible pure sine waves of fundamental frequency, and also that an effort be made to obtain transformers and to arrange connections of the same in such a manner as to reduce as far as practicable the distortion of wave-form."

Among the rules recommended by the committee and subsequently adopted by the California State Railroad Commission the following occurs:

"*Wave-Form of Rotating Machines*. The power company shall make every effort to obtain generators and synchronous motors for use on all parts of the system, giving, as nearly as reasonably possible, pure sine waves of voltage at fundamental frequency. In no case shall the deviation from a pure sine wave exceed the limit set forth in the Standardization Rules of the American Institute of Electrical Engineers."

"*Exciting Current of Transformers*. In order that the wave-shapes of voltage and current may be distorted as little as practicable by transformers, the main line transformers employed on circuits involved in a parallel and on future extensions of such circuits shall have an exciting current as low as is consistent with good practise, and in no case shall the exciting current at rated voltage exceed ten per cent of the full load current. Such transformers shall not be operated at more than ten per cent above their rated voltage."

This brings us directly to the question under consideration at this convention, that is, the criterion or the criteria by which irregularities of wave-form should be judged. The limitations and unsatisfactory character of the present Institute Standard of wave-form deviation were brought out in two papers presented in 1913; one by P. M. Lincoln and one by C. M. Davis (see TRANSACTIONS, volume 32, pages 765 and 775). Mr. Lincoln, in his paper, treated the subject wholly from the standpoint of the effect of wave-form distortion on electrical apparatus associated with power circuits. Looking at the subject from this standpoint Mr. Lincoln comments as follows:

" The Standardization Rules of the Institute state that the generator e.m.f. waves shall not depart from the sine shape by more than 10 per cent. The present form of the rule is not entirely satisfactory, since it does not penalize the higher frequency harmonics as much as they deserve. A 10 per cent deviation on the part of one of the higher harmonics is admittedly more dangerous than the same deviation on the part of a lower harmonic, but the existing rule does not recognize this. A modification of the existing rule so as to obtain such a recognition is desirable."

The papers before the present convention bring out very clearly the characteristics and limitations of the different criteria of wave-form distortion. The adaptability of these several factors as criteria of wave-form distortion, judged from the standpoint of inductive interference, is not touched upon by the authors of these papers. It is to this phase of the matter that we wish to draw particular attention.

Before considering the individual distortion factors mentioned in these papers it will be well to understand the desirable characteristics, from an inductive interference standpoint, of a distortion factor suited for rating the relative detrimental effect of different irregular wave-forms. A pure sine wave should obviously be chosen as the standard of comparison and for this purpose the r. m. s. value of the equivalent sine wave is suitable. The harmonics of current and voltage in a power circuit manifest themselves in an exposed telephone circuit as extraneous currents of the same frequencies in the telephone receivers at the terminals of the circuit. The detrimental effect of such extraneous currents on a telephone conversation is, aside from a certain annoyance due to the mere existence of the noise, to cause a decrease in the intelligibility of the conversation. Experimental determinations of this decrease in the intelligibility of a conversation corresponding to a given amount of extraneous current of a given frequency, have been made by the American Telephone and Telegraph Company at the request of this Committee. This decrease in intelligibility is evaluated in terms of the effect on the intelligibility of an increase in the length of the telephone circuit. The results of this investigation have shown that:

(a) Within the limits of experimental error the decrease in the intelligibility of conversation, caused by an extraneous current of a given frequency, is directly proportional to its magnitude.

(*b*) For a given amount of extraneous current the resultant decrease in intelligibility increases very rapidly with the frequency up to a certain maximum point and then decreases slowly. For frequencies ranging between the third and eleventh harmonics of 60-cycle systems this detrimental effect increases nearly as the square of the frequency. Beyond the frequency corresponding to the eleventh harmonic the curve gradually bends over, reaching a maximum at about 800 cycles and then gradually diminishing to about 85 per cent of maximum at 1500 cycles, beyond which point observations have not as yet been carried.

The facts just cited point to the desirability of penalizing the higher harmonics approximately in proportion to the square of their frequency up to a certain point. There is of course the question of the complex relationship between the relative magnitudes of different harmonics in the extraneous current of a telephone receiver and the relative magnitudes of these same harmonics at their origin in the power system. There are a number of factors which enter into this relationship; some tending to accentuate the higher harmonics and some tending to suppress them. Then, too, the relationship between wave-form of extraneous current in telephone receivers and wave-form at origin of harmonics in power system will vary to some extent with each and every case of inductive interference. Our present information does not permit us to generalize on this point. In the absence of more complete information we would suggest that in this connection the penalties for the existence of higher harmonics be rated somewhat in accordance with the law of their relative detrimental effect in a telephone receiver. This is undoubtedly conservative, as the net effect of the several factors is to emphasize the relative interference of the higher harmonics.

The above remarks have been concerned with the effects of given amounts of extraneous current of different single frequencies. In practise the noise in a telephone receiver is always caused by a complex current of several frequencies in various proportions. On this account it is necessary to consider the relationship between the detrimental effect of a complex wave and the detrimental effects of the individual components of that wave. Experimental investigations now under way are directed towards the empirical determination of this relationship. The results are not available as yet. In the absence of such information it has been assumed that this relationship follows the well known r. m. s. principle: that the value of the combined effect is equal to the r. m.s. of the individual effects.

There is still a further question which might be raised, that is, in regard to the effect of the phase relationships, among the several harmonics of the complex wave on the detrimental effect produced by that wave. Specific experiments directed at a determination of this point have not been thought necessary by the committee. A consideration of this problem shows its connection with the old controversy between Helmholtz and König concerning the influence of the phase of harmonics upon acoustic quality. An experimental investigation conducted by the Bureau of Standards in 1909 clearly supports the Helmholtz view, that quality is independent of phase relationship (see Bulletin of Bureau of Standards, Vol. 6, No. 2).

Summarizing the above discussion, the following appear to be the desirable characteristics of a distortion factor which will be useful as a criterion of the relative merits of different wave-forms when judged from the standpoint of their influence on inductive interference between power and telephone circuits:

(*a*) R. m. s. value of equivalent sine wave as standard of reference.

(*b*) Effect of a given harmonic weighted in direct proportion to its amplitude.

(*c*) Effect of different harmonics weighted in proportion to the square of their frequencies up to the eleventh or thirteenth harmonics of a 60-cycle system, higher harmonics to be given the frequency weighting of eleventh or thirteenth.

(*d*) Combined effect of different harmonics weighted in accordance with the r. m. s. value of their individual weights as determined by (*b*) and (*c*).

(*e*) Independence of phase relationships among harmonics.

With these characteristics in mind it will be well to take up each distortion factor discussed in the papers under consideration and compare its characteristics with those just mentioned.

Form Factor. It will be apparent at once that the form factor is totally unsuited as a measure of the distortion of wave-form from the standpoint of its effect on inductive interference. It does not meet any of the characteristics as set forth above and, as is pointed out in Prof. Bedell's first paper, is very indefinite as a measure of wave distortion.

Deviation Factor. This factor is unsuitable for a standard such as we have in mind because it is, in a sense, indefinite, having no exact relationship with the amplitude of the harmonics present and making no differentiation between harmonics of different orders. Any single harmonic may be present to the extent of practically 10 per cent and still be within the deviation limit. More than one harmonic may be present in the wave and the phase relationships among them may be such that while the sum of their maximum values may considerably exceed 10 per cent of the fundamental, the deviation will not exceed the 10 per cent limit. This factor obviously can not afford an accurate measure of the relative detrimental effects of different irregular wave-forms from the standpoint of inductive interference. Unfortunately, in this regard, it is the standard of the Institute and as such was accepted by this Committee in its recommendations for a rule upon the subject of wave-forms.

Harmonic Factor. There are certain merits in this factor in that it gives some weight to each harmonic, it weights the combined effect of all the harmonics in proportion to their r. m. s. value, and it is independent of the phase relationships of the different harmonics. Its severe drawback, however, is the fact that harmonics of different orders are all given equal weight.

Curve Factor. This factor is directly related to the harmonic factor and as such is subject to the same objections.

Peak Factor. Obviously this factor has little significance from the standpoint of inductive interference.

Integral Distortion Factor. The characteristic of this factor in weighting the individual harmonics in inverse proportion to their order makes it, of course, entirely unsuitable for our purpose.

Differential Distortion Factor. This factor, of all those mentioned in the papers under discussion, most nearly fulfils the requirements of a criterion of wave distortion based upon the bearing of such distortion upon the subject of inductive interference. Comparing its characteristics with those of our suggested distortion factor the following should be noted: Both have the r. m. s. value of the equivalent sine wave as the standard of reference. Both give weight to a given harmonic in direct proportion to its amplitude. Both give increasing weight to the higher harmonics. Both weight the combine effect of the individual harmonics in accordance with the r. m. s. law. Both are independent of the phase relationships of the several harmonics. They differ, however, in the exact weighting of harmonics as a function of their order. The differential distortion factor weights the harmonics on direct proportion to their order while for our suggested factor the harmonics up to the eleventh or thirteenth (60-cycle fundamental) would be rated in proportion to the square of their order. This suggests a modification of the differential distortion factor for this purpose, by substituting, in place of the first derivative of the wave, its second derivative. The use of such a modified distortion factor is, however, open to the objection that it is not so readily determined as the first derivative distortion factor. It could be determined by a knowledge of the wave-form as given by an oscillogram or simply by a knowledge of the amplitudes of the several harmonics as determined experimentally by a resonance method which has been much used by this Committee in its general investigation. With a knowledge of the magnitudes of the several harmonics as determined by either of the two methods mentioned, it may be said, however, that there is no particular advantage in using the second derivative over a set of empirically determined weights for the different harmonics which would rate them more truly in accordance with their relative detrimental effects, all factors considered.

Combination of Differential and Integral Distortion Factors. While the product of integral and differential distortion factors may be of real usefulness in certain computation work, such a combination for our purposes is open to objection on account of the characteristics of the integral distortion factor. Obviously, for our purposes, it offers no advantages over the differential distortion factor.

Before concluding these remarks we wish to draw attention, in connection with the general subject of wave-form, to the fact that the Standardization Rules do not specify a load condition under which the distortion factor or deviation factor of the voltage wave of a generator is to be measured. It is, however, universally customary, we believe, to rate the wave-form on the basis of no load on the machine. It is well recognized that the load condition has an important bearing on the wave-forms of both voltage and current. Furthermore, it is obvious that the wave-form under normal operating conditions and not that under the no load condition is the one with which we are most concerned. The relationship, therefore, between voltage wave-form under no load and under normal load is one which should be given careful consideration. We recognize the difficulty of specifying the wave form requirements under any other conditions than no load, since, in general, operating loads differ widely in their characteristics and different loads each have different effects upon the wave form derived from a given machine.

In conclusion to this review of the characteristics of distortion factors and their adaptability as measures of distortion from the standpoint of inductive interference, it is well to point out the practical importance of a reduction of harmonics and a closer approach to a pure sine wave of voltage and current in electrical power circuits. A material improvement in this respect, regardless of what criterion is taken as an index, would operate to reduce the requirements of transpositions and the restrictions of balance of power and telephone circuits which would be otherwise necessary to prevent harmful interference under existing conditions of wave form. We know that it is generally impracticable to ask that steps be taken to remedy such conditions in existing apparatus. It is our hope that substantial improvements may, however, be made in new machines by a due regard to the importance which should be attached to this phase of the subject of improvement in wave form. It is with this in mind that we take the present opportunity of calling attention to the importance of the problem from this standpoint, which though not new, has received little recognition heretofore.

Comfort A. Adams: Referring to the communication from San Francisco, it is only fair to the Standards Committee to say that they are quite aware of the limited usefulness of the term "form factor" as at present defined, and that it has long since ceased to convey the idea of the specific shape of the corresponding wave; but except in a few rare cases, this term is still useful in computing the maximum flux in a transformer core, (knowing the r.m.s. volts, the number of turns, the frequency and "form factor" of the e.m.f. wave). For this purpose the term will doubtless be used for some time to come, as it is very difficult to supplant an old established habit of usage. However, there is certainly great need of a term such as "distortion factor" or "per cent distortion" which will indicate with fair accuracy the degree in which an alternating wave differs from a sine wave. But this is not as easy as it sounds. A paper was presented before the Institute at the first midwinter convention, February, 1913, by Mr. C. M. Davis, dealing with this subject and suggesting a definition of "per cent distortion" as well as a method of determining it. After much discussion it was decided to postpone the subject. It is needless to say that the Standards Committee realizes the importance of this subject and will do its best to present a satisfactory terminology.

L. W. Chubb: The first paper on Form Factor is apparently a very simple treatment. The subject, however, is not as simple as the paper indicates. A little over a year ago in a brief article on several factors of this kind I attempted to cover form factor in somewhat the same way, but it became so complicated that it was struck from the manuscript.

The definition as given at the opening of the first paper is incomplete and under certain conditions is wrong.

The average value used in the calculation of form factor must be the average of ordinates between certain symmetrical zero values, which will give the greatest average. In the case of odd harmonics only, these zero values are a half-cycle apart, but with even harmonics the zeros may not be a half-period apart. A single odd harmonic which is more than $\frac{1}{N}$ of the amplitude of the fundamental may, and an odd harmonic which is greater than the fundamental must, reverse the resultant curve and make it pass through zero more than twice per cycle. Such a wave causes more than one maximum and one minimum value per cycle in the integral or flux wave; so that iron in a transformer is carried through a major and two or more minor hysteresis loops per cycle, causing a higher loss than that indicated by the form factor corresponding to the largest average between any two symmetrical zero points.

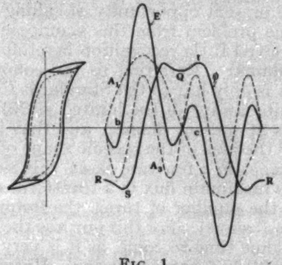


Fig. 1

Prof. Bedell calls special attention to the combination of a fundamental wave and a third displaced 60 fundamental degrees. This would be:

$$A_1 \sin \theta + A_3 \sin 3(\theta - 60)$$

or $$A_3 \sin \theta - A_3 \sin 3\,\theta$$

In Fig. 1, A_3 is 75 per cent of A_1 and it will be noted that the third component of voltage, since it has an amplitude greater than one-third of the fundamental, reverses the resultant voltage E and makes it pass through zero four times per cycle. The flux which is the integral of the voltage wave is $K\,(-A_1 \cos \theta + \frac{A_3}{3} \cos 3\theta)$ and is shown in the heavy curve ϕ. Such a flux wave will carry an iron core through the hysteresis cycle shown to the left of the curves. The author's results give a form factor of 1.819 derived from an average value obtained by integrating the voltage wave from 0 to π. Such a result would indicate the hysteresis loss of a loop (shown dotted) having tips equal in amplitude to the points, Q, R, on the flux curve, which is obviously much too low. If, as in the present definition of form factor, we integrate for the average value from the zero point (b) to the zero point (c) the two small areas of the voltage wave included, one plus and one minus will cancel and the average value will be measured by the area of the large positive lobe of the wave. Form factor so measured will indicate a loss corresponding to a loop having tips of amplitudes S and t, but will still be too low by the amount of the area of the two minor loops caused by the dip in the flux.

The author also calls attention to the case in which A_3 is three times as great as A_1 and speaks of a form factor of infinity. Fig. 2 shows the curves for this case and it is evident that the average voltage is zero when integrated from 0 to π, simply because the two negative areas of the wave are together equal to the large positive area. If, as before, the integration is taken from b to c the negative and positive small lobes of the included voltage wave will cancel and the average will be measured by the area of the large positive lobe. In this case the loss is nearly twice that caused by the major loop and the standard definition of form factor gives a value which in the equation for hysteresis loss is useless.

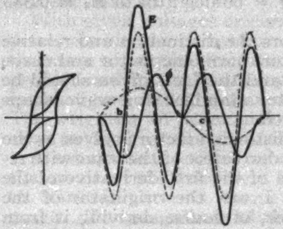


FIG. 2

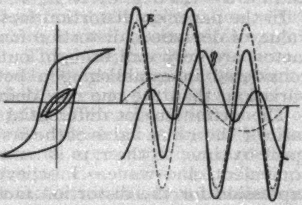


FIG. 3

In Figs. 1 and 2 we have considered the lag of the third component as 60 fundamental degrees. If there is no lag both waves will start from zero together and the conditions will be as shown in Fig. 3. In this case the largest average comes when integrating from 0 to π. The flux variation will give minor loops displaced sideways and approximately symmetrical to the H axis.

With even harmonics present in the voltage wave the two lobes of a cycle may be of equal time length, but the plus and minus amplitudes of the integral or flux wave will not be alike and there will result a displaced hysteresis loop having an area in excess of the symmetrical loop of the same double amplitude and giving losses in excess of those indicated by the r. m. s. voltage and form factor. In other cases with even harmonics, the two lobes may be very different in shape, of different length and yet the flux waves will have the same symmetrical amplitudes and the loss will accurately agree with that indicated by the r. m. s. voltage, and the form factor figured between symmetrical zero values of the wave.

On account of these indeterminations and the uselessness of form factor for very distorted waves, it should be considered for waves which cross zero only twice per cycle and which contain only odd harmonics. Transformer and other magnetic cores are today subjected to waves containing even harmonics and very distorted odd harmonics waves, but the form factor as now defined is of no use in these limited and special cases.

In his solution, the author has made the mistake of integrating for the average value between the zero points of the fundamental component, instead of the zero points of the composite wave. A few checks of points shown in the curves indicate that this method has been followed out in working up the curves of Figs. 1 to 7 inclusive and they are, if we are to consider the generally accepted definition, in error for all points except values for $\theta = 0$ up to $E_3 = 1$, where $\theta = 60$ deg., up to $E_3 = 0.333$ and for $\theta = 120$ deg. up to $E_3 = 1$.

In the paper on distortion factors the distinction and relative value of deviation, distortion factor, harmonic factor and curve factor, are very well brought out and the facts given should be considered in establishing a better standard for wave shape variation, than the one now defined.

The definition for differential distortion factor is given as the ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r. m. s. value of the first derivative of the equivalent sine wave. I believe I was the originator of the expression for the distortion factor, of course deriving it from Mr. Davis's condenser test, distortion ratio. I gave the definition to the Standards Committee as the ratio between the r. m. s. value of the first derivative of the wave and the r. m. s. value of the wave itself. There is no good, I take it, in putting in the denominator, the derivative of the equivalent sine wave, because it is exactly the same as the r. m. s. value of the wave itself. In the same way in the case of Prof. Bedell's new constant we may invert and define cos φ as the ratio of the mean square of the wave to the product of the differential and integral of the wave.

In the last paper, by Mr. Mizushi, I think we have a very novel and interesting solution of non-sinusoidal currents. The derivation and graphical representation of Figs. 4 and 5 are especially interesting, and since they are built on a good mathematical foundation I believe this method of calculation will come into general use, provided we can easily determine the constants delta and sigma.

Harold S. Osborne: A communication has been read from the Joint Committee on Inductive Interference calling attention to the predominant effect of the high-frequency components of the current and voltage waves of power systems in the production of noise in telephone circuits by induction. As a matter of fact, the noise induced in telephone circuits by power circuits would practically vanish if all power voltages and currents were pure sine waves. There are thousands of miles of parallel between telephone pole lines and high-tension power circuits, and reduction in the efficiency of telephone circuits, due to induced noise, is quite general. It is not believed, however, that there is in the whole country a single case where any important part of the noise in the telephone circuits is due to the sine wave 60-cycle or 25-cycle components of the induced currents. The committee has suggested that in view of these facts an interference factor be considered in taking account of wave distortion, in which factor the harmonics should be weighted proportional to the square of their order up to a frequency of 700 or 800 cycles, and then weighted uniformly for higher frequencies.

The two curves given illustrate the reason for that suggestion, and show that the weighting suggested for the higher harmonics is very moderate from the standpoint of inductive interference.

Refer first to Fig. 4.

With given voltages or currents of different frequencies in the power circuit, the current produced in the telephone line, within the range of frequencies with which we are concerned, is roughly proportional to the frequency. This is represented by curve *A* in this figure, which is drawn with 60-cycles representing unity. The weighting of harmonics which is given in this curve is the same as that given in computing the differential distortion factor.

A second factor which must be considered is due to the fact that some of the telephone terminal apparatus is designed not to transmit currents having frequencies below the telephonic range. The magnitude of this factor for one type of telephone terminal apparatus is represented by curve *B* in the figure, which is drawn so as to pass through unity at 60-cycles. This curve shows the ratio of current in the receiver at any frequency to current in the receiver at 60 cycles for a given line current. It will be seen that for frequencies below about 200 this type of telephone terminal apparatus is designed to largely eliminate the current, so that at low frequencies the percentage of the line current which gets into the telephone receiver is small.

A third factor which enters into the production of inductive interference and which also varies largely with the frequency is the amount of interfering effect which is caused by a given amount of current in the telephone receiver. This is the effect which is referred to by the committee. It is represented in Fig. 4 by curve *C*, which is also drawn with unity at 60 cycles, and which shows the relative amount of interfering effect which is caused by currents in the telephone receiver of a given magnitude and of different frequencies. The interference effect is measured by the effect on the intelligibility of telephone conversations. Curve *C* is based on an experimental investigation which was carried out under direction of the committee.

The total relative effect of currents or voltages in the power circuit of a given magnitude and of different frequencies can be represented approximately by the product of these three curves. This product is represented by Fig. 5, which is drawn to a scale in which 60 cycles is unity. It will be seen that below 180 cycles the inductive effects practically disappear, that they increase very rapidly up to a frequency of 800 or 1000 cycles, and less rapidly up to about 1600 cycles. At frequencies above 1600 the effect would probably begin to decrease.

These curves would not apply exactly to specific cases, and can give an idea only of the order of magnitude of the effect of different frequencies. Many of the factors depend on the particular conditions assumed. There are other factors which also enter into the problem in particular cases. The most important of these is the manner in which the currents and voltages occur in the power circuit, namely, whether they are balanced between the line wires of the power circuit or are impressed between the line wires and the ground. For example, in a three-phase star-connected system, with a grounded neutral, the third harmonic and its multiples do not appear between the line wires, but appear between all the line wires and the ground. For a given frequency, currents which occur in that way have a much greater inductive effect on neighboring circuits than currents which appear between the line wires and which are balanced with respect to the ground.

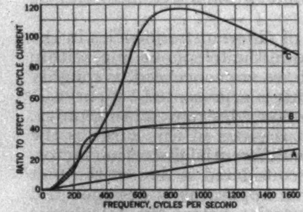


Fig. 4—Relative Effect of Currents of Different Frequencies

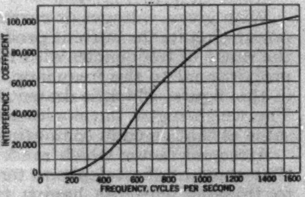


Fig. 5—Variation of Interference Coefficient with Frequency

By the use of some such curves as these, or the more moderate curve suggested by the committee, we could compute an interference factor, as they suggest. The committee suggests that in combining the interfering effect of a number of currents of different frequencies occurring in the same wave, the effect be added according to the r. m. s. law. It might be said that although the direct experimental work to test this law, which was spoken of in the committee communication, has not yet been carried out, there is a certain amount of evidence to support that suggestion. It has been found, for example, that the combined effect of a number of complex noise currents in a telephone receiver is approximately equal to the r. m. s. of the effects of the individual complex noise currents.

To many who have not come into contact with telephone work, a discussion of harmonics in the power circuit having frequencies of 1000 or more might seem to be purely academic. I think the curve shown in Fig. 5 illustrates why that is not the case. In most of the cases of noise in telephone circuits which have been carefully analyzed, the noise has been found to be due to the combined effect of a great many currents of frequencies covering a wide range, components up to 1200 cycles or more being important in the production of the total effect. In some cases the noises are due predominantly to one or two frequencies. In such cases the predominant frequencies are usually of fairly high order and are frequently due to the slots in the armatures. Slot harmonics are very often of a frequency well within the most sensitive range for the production of interference in telephone circuits. For example, a 60-cycle three-phase generator, with two slots per pole per phase, has slot harmonics, when they occur, of the 11th and 13th order, which are well within the sensitive range. One case comes to mind in which the slot harmonics in a machine of this sort were large enough so that when the particular machine was operated the nearby telephone circuits were put out of service, although when other machines were operated on the same power lines no effect was noticeable. In this case the interference factor of the machine causing the trouble, as figured from Fig. 5, would be something over 3000. The pole pieces of the machine were in this case modified, and in that way the interference factor was reduced to about one-half of its former value. A new machine which was designed for the same service had an interference factor of about 500, or about one-sixth of that of the original machine. Another case comes to mind in which a 25-cycle machine had a large 35th or 37th harmonic. It had eighteen slots per pole, which was the cause of the harmonic, and produced a sufficiently large harmonic of that order to cause a very large disturbance in telephone circuits.

The curve of Fig. 5 is drawn with unity at 60 cycles. On that curve 25 cycles has an ordinate of approximately 0.03. This fact indicates why, with a given wave shape, the interference from 25-cycle systems is much less than that from 60-cycle systems.

The interfering effects of the components of current of high frequency are, of course, equally large if they occur in d-c. machines, as is sometimes the case. This fact suggests that a measure of the interference effect of a machine can best be obtained by figuring the equivalent volts or amperes at a given frequency of the components which enter into the interference, weighting them in accordance with some such curves as have been shown. Any interference factor based on the curves given above, or such as suggested by the committee has the disadvantage that it is somewhat difficult to measure or compute. It does not seem, however, that this is a sufficiently important difficulty to prevent its use. Admittedly the production of pure sine waves is a practical impossibility, but it is believed that it would be easily possible, and a true economy, to considerably reduce the interference producing power of electrical machinery as now constructed.

W. V. Lyon: I agree with Dr. Bedell that the form factor of an alternating e. m. f. has little or no important significance. Entirely different wave shapes may have identical form factors. For example, one that consists of a fundamental and a 75 per cent third harmonic which is in phase with it has the same form factor as a pure sine wave. We may even be misled when considering its probable effect on the hysteresis loss in a transformer.

The effective or r. m. s. value of an alternating e. m. f. is equal to the r. m. s. of its several harmonic components. It depends in no way upon their phase relations. The average value of a non-sinusoidal wave is not by any means as easily found even when we know the harmonic components and their phase relations. Article 16 of the revised Standardization Rules says:

" Form factor is the ratio of the r. m. s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, the zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine-wave is 1.11."

This definition of average value follows from the established principle concerning the relation between the flux linking a circuit and the voltage produced in the circuit by the flux.

$$e = -N \frac{d\varphi}{dt}$$

The flux is a maximum when its rate of change is zero, that is, when e is zero. Thus, the average voltage and the maximum flux are found by integrating the voltage curve between points at which e is zero and which are a half wave length apart. If the curve crosses the axis at more than two points in a cycle, this integration will give different values. The proper one to use is, of course, that which gives the largest value.

If the voltage wave is symmetrical, the result of this integration is:

$$E_{av} = 4\, N f\, \phi_m\, 10^{-8}$$

N is the number of turns, f, the frequency and ϕ_m, the maximum flux that links the circuit.

If the instantaneous voltage is

$$e = E_1 \sin x + E_3 \sin 3\,(x + \theta_3) + E_5 \sin 5\,(x + \theta_5) + \ldots\ldots,$$

the average value of e is not in general

$$E_{av} = \frac{1}{\pi}\int_0^{\pi} e\,dx \qquad \textbf{(1)}$$

but

$$E_{av} = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} e\,dx \qquad \textbf{(2)}$$

where α is the point at which the e. m. f. is zero and is further qualified as stated in Article 16. If simplicity is desired it is unfortunate that the average value is so defined, since it makes an exact analytical solution practically impossible in all but a few cases. The simplest method is to plot the wave and thus determine the zero points—*i.e.*, find α. The average value may then be found from the area of the curve or from the value of the integral—equation (**2**).

If the phase angles θ_3, θ_5, etc. are all zero or equal to $\pm\frac{\pi}{3}$, $\pm\frac{\pi}{5}$ etc., respectively, equation (**2**) reduces to equation (**1**) in some cases.

Let

$$e = E_1 \sin x + E_3 \sin 3\,x + E_5 \sin 5\,x + \ldots\ldots.$$

where the coefficients E_3, E_5, etc., may be either positive or negative.

If the slope of this curve is positive when $x = 0$, it is probable in all practical cases that equation (**1**) may be used. If, however, the slope of this curve is negative when $x = 0$, it is probable in all practical cases that equation (**1**) is *not* true. For example, suppose that we have an e. m. f. consisting of a fundamental and a third harmonic that are either in phase or in opposition.

$$e = E_1 \sin x + E_3 \sin 3\,x$$

E_3 may be either a positive or a negative number.

$$\frac{de}{dt} = E_1 \cos x + 3\,E_3 \cos 3\,x$$

when $x = 0$, $\quad \frac{de}{dt} = E_1 + 3\,E_3$

If E_3 is positive the curve slopes upward when $x = 0$ and equation (**1**) applies. See Fig. 6. Even if E_3 is greater than E_1 so that the curve crosses the axis more than twice in a cycle, this equation will still hold.

If, however, E_3 is negative and greater than one-third of E_1 the curve slopes downward when $x = 0$ and equation (**1**) does *not* apply. See Fig. 7. The area from 0 to π is less than the area from α to $\alpha + \pi$ by an amount equal to twice the area from 0 to α. If we should apply equation (**1**) to the case where the third harmonic is three times the fundamental and in opposition to it, the form factor would be infinite, since the area from 0 to π is zero.

By (**1**) $$E_{av} = \frac{1}{\pi}\int_0^{\pi} (E_1 \sin x - 3\,E_1 \sin 3\,x)\,dx = 0$$

This is of course an extreme case.

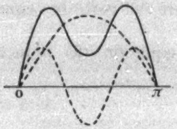


Fig. 6

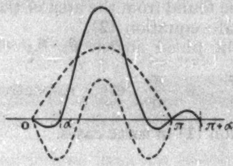


Fig. 7

In order to find the true average value we must determine where the curve crosses the axis beyond $x = 0$.

That is:

$$E_1 \sin x - 3\,E_1 \sin 3\,x = 0$$

or

$$\sin x - 3\,(3 \sin x - 4 \sin^3 x) = 0$$

$$12 \sin^3 x = 8 \sin x$$

$$\sin x = \pm\sqrt{\frac{2}{3}}$$

$$= \pm\,0.817$$

$$x = 54.8 \text{ degrees}$$

Therefore, in equation (**2**)

$$\alpha = 54.8 \text{ degrees}$$

The true average value by equation (**2**) is

$$E_{av} = \frac{E_1}{\pi}\int_{\alpha}^{\alpha+\pi} (\sin x - 3 \sin 3\, x)\, dx$$

$$= \frac{2\, E_1}{\pi} (\cos \alpha - \cos 3\, \alpha)$$

$$= \frac{2\, E_1}{\pi} (\cos 54^\circ.8 - \cos 164^\circ.4)$$

$$= \frac{2\, E_1}{\pi} (0.577 + 0.963)$$

$$= 0.972\, E_1$$

The r. m. s value of this voltage is

$$E = \frac{\sqrt{E_1^2 + (3\, E_1)^2}}{\sqrt{2}}$$

$$= 2.23\, E_1$$

The form factor is

$$f = \frac{2.23\, E_1}{0.972\, E_1} = 2.30.$$

If the voltage had contained any higher harmonic than the third it would not have been easy to calculate the value of α.

Thus it appears, in general, that the form factor can only be simply calculated from the analytical expression of the voltage when the harmonic components are either in phase or in opposition and the curve does not cross the axis at more than two points in a cycle. Like practically all rules, this has some exceptions. If, for example, the wave consists of a fundamental and a third harmonic greater than but in time phase with it, the average value should be calculated by equation (**1**), even though the curve crosses the axis at more than two points in the cycle.

If the wave consists of a fundamental and a 75 per cent third harmonic which is in phase with it, the form factor is the same as for a sine wave. Or, if the wave consists of a fundamental, a 5.3 per cent third harmonic in opposition to it and a 25 per cent fifth harmonic in phase with it, the form factor will be the same as for a sine wave. The first example might be called a flat-topped and the second a peaked wave. See Figs. 8 and 9.

The flux, ϕ, will have as many maximum values as the voltage, e, has zero values. Thus if the voltage crosses the axis more than twice in a cycle the flux will have more than two maximum values in a cycle and the hysteresis curve will contain smaller loops. In such a case the hysteresis loss will be greater than the maximum flux would tend to indicate, and the value of the form factor may be of little significance, especially in extreme cases. If the voltage wave, for example, should consist of a fundamental and a third harmonic which is in phase opposition to, and greater than one-third of it the hysteresis loop will contain smaller loops within itself. If the voltage wave consists of a fundamental and a third harmonic which is in phase with it, the third harmonic must be greater than the fundamental in order that the hysteresis loop shall contain smaller loops within itself. An e. m. f. which crosses the axis more than twice in a cycle will probably have a greater form factor than a sine wave. This would indicate a smaller maximum flux and thus an apparently smaller core loss. But the interior loops on the hysteresis curve will cause a greater loss than the maximum flux indicates. The effect of form factor, however, will probably predominate.

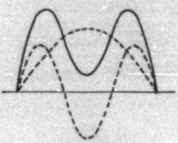


FIG. 8

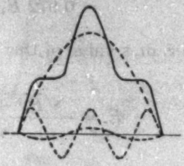


FIG. 9

If $e = E_1 \sin x + E_3 \sin 3\,x + E_5 \sin 5x + \,.\,.\,.\,.\,.\,.\,.\,.\,.$

the effective voltage is:

$$E = (E_1^2 + E_3^2 + E_5^2 + \,.\,.\,.\,.)^{\frac{1}{2}} \Big/ \sqrt{2}$$

and the average voltage is:

$$E_{av} = \frac{2}{\pi}\left(E_1 + \frac{E_3}{3} + \frac{E_5}{5} + \,.\,.\,.\,.\,.\right)$$

provided the wave does not cross the axis more than twice in a cycle.

$$f = \frac{\pi}{2\sqrt{2}} \frac{(E_1^2 + E_3^2 + E_5^2 + \ldots\ldots\ldots)^{\frac{1}{2}}}{\left(E_1 + \frac{E_3}{3} + \frac{E_5}{5} + \ldots\ldots\right)}$$

If the form factor is the same as for a sine wave, viz., $\frac{\pi}{2\sqrt{2}}$,

$$(E_1^2 + E_3^2 + E_5^2 + \ldots\ldots) = \left(E_1 + \frac{E_3}{3} + \frac{E_5}{5} + \ldots\right)^2$$

If all of the harmonics higher than the third are absent this becomes

$$E_1^2 + E_3^2 = E_1^2 + \frac{2}{3} E_1 E_3 + \frac{E_3^2}{9}$$

$$\frac{8}{9} E_3^2 = \frac{2}{3} E_1 E_3$$

$$E_3 = \frac{3}{4} E_1 \qquad \text{(See Fig. 8.)}$$

If all of the harmonics higher than the fifth are absent, we have

$$E_1^2 + E_3^2 + E_5^2 = E_1^2 + \frac{E_3^2}{9} + \frac{E_5^2}{25} + \frac{2}{3} E_1 E_3 + \frac{2}{5} E_1 E_5 + \frac{2}{15} E_3 E_5$$

Solving for E_3 gives

$$E_3 = \frac{\left(\frac{2}{3} E_1 + \frac{2}{15} E_5\right) \pm \sqrt{\left(\frac{2}{3} E_1 + \frac{2}{15} E_5\right)^2 - \frac{32}{9}\left(\frac{24}{25} E_5^2 - \frac{2}{5} E_1 E_5\right)}}{\frac{16}{9}}$$

If we put $\frac{E_3}{E_1} = a$ and $\frac{E_5}{E_1} = b$ this reduces to:

$$a = \frac{9}{16}\left\{\left(\frac{2}{3} + \frac{2}{15}b\right) \pm \sqrt{\left(\frac{2}{3} + \frac{2}{15}b\right)^2 - \frac{32}{9}\left(\frac{24}{25}b^2 - \frac{2}{5}b\right)}\right\}$$

This equation shows the relation that must exist between the harmonics in order that the form factor shall be the same as for a sine wave.

If $b = +0.25$, the solution for a is: $a = -0.0532$.
(See Fig. 9.)

A number of years ago the writer was interested in working out the conditions for series and parallel resonance when a non-sinusoidal voltage is impressed on the circuit. This is a special case of the general problem that Mr. Mizushi discusses. The method used regarded the problem from a slightly different angle. If a non-sinusoidal voltage is impressed on any circuit consisting of a combination of a *constant* resistance, *constant* inductance and *constant* capacity, the resulting current will consist of a number of harmonic components, each of the same magnitude it would have if the corresponding harmonic component in the voltage acted alone. The true or ohmic resistance of a metallic circuit varies only with the temperature. The apparent resistance varies with the frequency and if there is iron or other conducting material nearby, it will be increased over its true value on account of hysteresis and eddy-current losses. The inductance of a circuit, even if there is no iron or other conducting material nearby, depends upon both the resistance and the frequency. If there is any iron present the inductance is a complex function of its permeability. The capacity of a condenser is generally regarded as being independent of the frequency and the dielectric strain. If, however, there are dielectric losses or if the condenser is a leaky one, the equivalent capacity is not constant. If these limitations are neglected the calculated results may be of little value in some cases. Their cognizance, however, may make the solution extremely difficult if not impossible. In what follows it will be assumed that the "constants" of the circuit are truly constant.

For a series circuit, such as is illustrated in Fig. 10, the relation for the nth harmonic voltage and current is

$$E_n^2 = I_n^2\left((r_1 + r_2)^2 + \left(n\,L\,\omega - \frac{1}{n\,C\,\omega}\right)^2\right)$$

$$= (r_1 + r_2)^2 I_n^2 + (L\,\omega)^2 n^2 I_n^2 - \frac{2L}{C} I_n^2 + \left(\frac{1}{C\omega}\right)^2 \frac{I_n^2}{n^2} \quad (3)$$

The summation to include all of the harmonics is

$$E^2 = \sum E_n^2 = (r_1 + r_2)\, I^2 - \frac{2\,L}{C}\, I^2 + (L\,\omega)^2 \sum n^2 I_n^2$$

$$+ \left(\frac{1}{C\omega}\right)^2 \sum \frac{I_n^2}{n^2}$$

This is equation (**5**) in a slightly different form. As Mr. Mizushi points out, the distortion factors for current are of no practical importance since they cannot be calculated until the various harmonic components of the current are known and at that time the problem has been solved. If the condenser C is a leaky one, it is equivalent to closing the switch so that r_3 is in parallel with C. The apparent series resistance and capacity between the points d and b now depend upon the frequency and are no longer constant, and equation (**5**) does not apply.

$$r' = \frac{r_3}{1 + r_3^2\, n^2\, C^2\, \omega^2}$$

This is a function of the frequency.

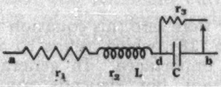


FIG. 10

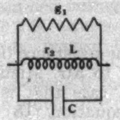


FIG. 11

The apparent capacity is

$$C' = \frac{1 + r_3^2\, n^2\, C^2\, \omega^2}{r_3^2\, n^2\, \omega^2\, C^2}\, C$$

This is also a function of the frequency.
Solving equation (**3**) for I^2 gives:

$$I^2 = \sum I_n^2 = \sum \left(\frac{E_n^2}{(r_1 + r_2)^2 + (L n\,\omega)^2 - \frac{2\,L}{C} + \left(\frac{1}{C n\,\omega}\right)^2} \right)$$

The maximum value of I would be found by differentiating this expression with respect to C. The resulting equation is

$$\sum \left(\frac{E_n^2 \left(- \frac{2\,L}{C} + 2\,\frac{n\,\omega}{(n C\,\omega)^3} \right)}{\left((r_1 + r_2)^2 + (n L\,\omega)^2 - \frac{2\,L}{C} + \left(\frac{1}{\omega C n}\right)^2 \right)^2} \right) = 0$$

The solution of this equation for C is difficult. It is thus not practical to calculate a value of capacity that will give the maximum current when a non-sinusoidal voltage is impressed on the circuit. An approximate value might be found by plotting the current against the capacity.

The parallel combination of *constant* resistance, inductance and capacity is somewhat simpler to solve. See Fig. 11. The nth harmonic of the current is determined by

$$I_n^2 = E_n^2 \left(\left(g_1 + \frac{r_2}{r_2^2 + n^2 L^2 \omega^2} \right)^2 + \left(\frac{n L \omega}{r_2^2 + n^2 L^2 \omega^2} - n C \omega \right)^2 \right)$$

The square of the total current is

$$I^2 = \sum I_n^2 = \sum E_n^2 \left(\left(g_1 + \frac{r_2}{r_2^2 + n^2 L^2 \omega^2} \right)^2 \right.$$
$$\left. + \left(\frac{n L \omega}{r_2^2 + n^2 L^2 \omega^2} - n C \omega \right)^2 \right)$$

If the resistance of the inductor were zero this equation would reduce to Mr. Mizushi's equation (**18**), which refers to a very special case that is of doubtful importance. In general, the g in equation (**18**) is not constant but depends upon the frequency, and, if there is iron in the magnetic circuit, upon the magnitude of the applied voltage.

The condition for resonance is easily found in this case: The condition is

$$\frac{\partial}{\partial C} I^2 = 0$$

This reduces to

$$\sum E_n^2 \left(\frac{n L \omega}{r_2^2 + n^2 L^2 \omega^2} - n C \omega \right) n \omega = 0$$

From which

$$C = L \left[\frac{\displaystyle\sum \frac{n^2 E_n^2}{r_2^2 + n^2 L^2 \omega^2}}{\displaystyle\sum n^2 E_n^2} \right]$$

For this value of capacity the current will be a minimum.

For a sine wave this becomes the well-known relation

$$C = \frac{L}{r_2^2 + L^2 \omega^2}$$

A numerical example of this principle proves interesting. A reactor which has a resistance of 5 ohms and an inductance of 0.1 henry is connected in parallel with a variable capacity across a 60-cycle, 305.5-volt circuit. If the applied voltage is a sine wave, the capacity which gives a minimum current is 69.1 microfarads. The least value of the current is 1.06 amperes. If the applied voltage consists of a fundamental, a third harmonic and a fifth harmonic whose effective values are 300 volts, 50 volts and 30 volts respectively, the capacity which gives a minimum current is 47.9 microfarads. The least value of the current is in this case 4.53 amperes—an increase of 290 per cent. If the resistance of the reactor is neglected, the calculated minimum value of the current is 4.25 amperes for a capacity of 48.7 microfarads. This is about 6 per cent less than the actual value. If the resistance of the reactor had been 50 ohms, the minimum current would have been 4.71 amperes for a value of the capacity of 18.5 microfarads. In the latter case if the applied voltage were sinusoidal the minimum current would be 3.90 amperes for a capacity of 25.5 microfarads. An air-core reactor usually has a comparatively high ratio of resistance to inductance. Iron in the magnetic circuit is practically necessary if the ratio is to be made low, but in this case neither the inductance nor the apparent resistance is constant.

To the writer it seems that the method of solution in which the harmonic components are calculated separately is, in general, superior, when considered from the combined standpoints of the ease, the accuracy and the completeness of the results.

W. I. Middleton and C. L. Dawes: Probably no type of load causes more severe reactions upon alternator e. m. f. waves than those brought about by cable testing. The load inherently is single phase and this alone causes pulsating armature reaction. The exciting current of the step-up transformer may contain a large percentage of harmonics, if the transformer is operated at the high densities common to testing transformers. These two effects may introduce harmonics into the voltage wave even if it be sinusoidal at no load. The cable capacity accentuates these harmonics in the current wave and more distortion follows; these reactions may be cumulative until checked by the counter-reactions of the alternator or of the circuit.

As was shown by the writers, in a paper* presented at the Detroit Convention of last year, many wide departures from a sine wave may be encountered under the foregoing conditions.

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*"Voltage Testing of Cables," W. I. Middleton and Chester L. Dawes, TRANS. A. I. E. E., Vol. XXXIII, 1914, p. 1185.

Even with the same cable the wave is influenced by such factors as the method of connecting the transformer coils, whether in series or in parallel. For instance, Fig. 12 shows the voltage and current waves, when a 0.1-microfarad cable was connected to the transformer secondary. The voltage wave is commercially sinusoidal and the current has no appreciable harmonic beyond the third. Fig. 13 shows an oscillogram taken with the same cable except that the transformer ratio was halved, the voltage upon the cable being maintained at its previous value. It will be observed that voltage wave has even a very appreciable fifth harmonic, and the *peak factor* has increased to 1.81. The third harmonic of the current wave has an amplitude of about 50 per cent greater than that of the fundamental.

Fig. 14 illustrates another point brought out by Prof. Bedell, the fact that a voltage wave may contain very appreciable harmonics, yet the phase relation of the harmonics is such that the *peak factor* is equal 1.41 as in a sine wave.

It is obvious that with such a wide variation of peak factor, cable testing might be very unsatisfactory from the standpoint of accuracy. As Prof. Bedell has demonstrated, the magnitude and number of harmonics alone have no bearing on the peak voltage. Some simple and direct method of measurement of peak values is necessary for our work. We find it quite hazardous measuring the peak voltage with a spark gap, because the breakdown of the gap is almost certain to cause circuit oscillations destructive to the cable. Further, the gap is not adapted to commercial testing where a large number of tests must be made in a comparatively short time by non-technical men. To put the testing upon a more accurate basis, a peak voltmeter based upon the oscillograph was devised. The instrument is placed directly upon the switchboard. It can be easily and accurately manipulated by the testing room employee.

Harmonics may cause troubles other than the mere distortion of the wave. Surges and premature break-downs may occur when the voltage is being raised, due to transients or to so-called static discharges over the end of the cable. A disturbance of this nature is shown in the ripples that appear in Fig. 14. Isolated cables may puncture, due to their being in close magnetic coupling with the cable under test. It was therefore considered advisable to install a generator having a sine wave under all conditions of load, if one was obtainable. Such a machine was built under the direction of Professor C. A. Adams. Even under the most severe conditions of load, no appreciable departure from a sine wave has as yet been observed. The armature is a standard three-phase stator, two of the phases only being utilized. The field has a special distributed winding and is surrounded by dampers. If a generator of this size can be designed to maintain a sine wave under these severe conditions of load, surely the larger units with practically balanced polyphase loads can be designed to do likewise.

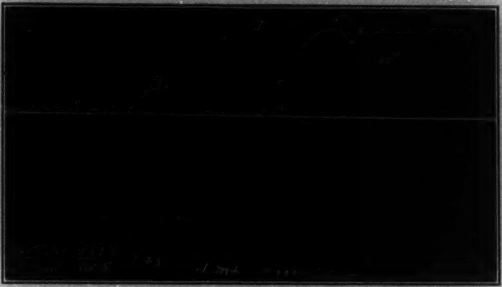


FIG. 12 [MIDDLETON AND DAWES]

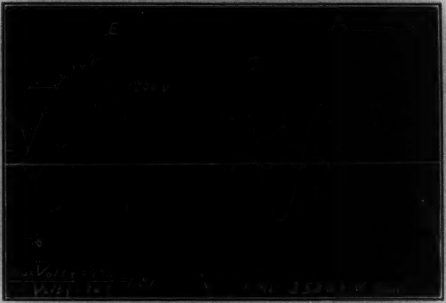
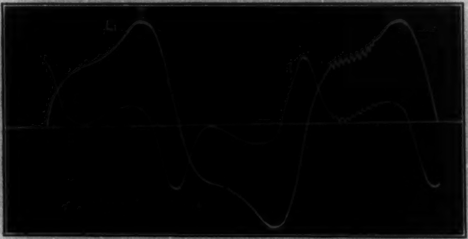


FIG. 13 [MIDDLETON AND DAWES]



[MIDDLETON AND DAWES]

FIG. 14

In view of recent investigations of telephone disturbances; of inexplicable surges and breakdowns in power systems, especially cable systems; of the difficulties encountered in testing long cables installed; and of the increasing refinements in electrical measurements, we believe that in the near future, alternator specifications will call for a fairly rigid adherence to a sine wave.

Comfort A. Adams: Of course Mr. Dawes does not mean literally a perfect sine wave, but practically a perfect sine wave. The machine referred to actually gives under all conditions of single-phase load a terminal voltage wave so nearly sinusoidal that no harmonics are detectable in oscillograms of either voltage or cable charging current, by a trained observer.

In regard to the first two curves presented by Mr. Dawes, the change, when the transformer connections and the excitation of the alternator were changed, was, I feel quite sure, not due to the change in the armature reaction, so much as to the fact that the change from series to parallel connection in the transformer coils changed the equivalent inductive-reactance of the alternator and transformer, which is substantially in series with the capacity-reactance of the cable. I found this same phenomenon in a number of other cases of cable testing apparatus. There was distinct evidence of resonance between the capacity-reactance of the cable and the inductive reactance of the transformer and alternator coming at different stages of the load for the different harmonics. As you increase the capacity, the lower harmonics appear and the higher harmonics are absorbed in the inductive reactance. In fact, sufficient series reactance will absorb such a large part of all the harmonic voltages that may have been produced in the alternator, that the voltage across the cable is substantially sinusoidal. Armature reaction undoubtedly does come into play, but I think in this case the change in the inductive reactance was responsible to a large extent for the difference in the magnitude and frequency of the harmonics appearing at the transformer terminals. Another disturbing function in such a case is the distorted exciting current of the transformer.

C. L. Dawes: Referring to these particular oscillograms, the best generator wave was obtained when the circuit was nearly in resonance with the fifth harmonic. For instance, in Fig.12, the natural frequency of the cable and transformer circuits was 110 cycles per sec., whereas the frequency of the fifth harmonic was 115 cycles per sec. corresponding to the fundamental frequency of 23 cycles per sec. In Fig. 13, which shows a very high degree of wave distortion, the natural frequency of the circuit was 215 cycles per sec. corresponding nearly to the frequency of the ninth harmonic. Of course it was impossible to make an exact calculation of the resonant circuit frequency, due to the variable nature of the permeability of the transformer iron, which was operated at a very high density, and also to the fact that the synchronous reactance of a single-phase alternator is an indeterminate quantity. Our explanation of the best wave shape being obtained under conditions tending to accentuate the lower harmonics is that the transformer iron was operated at such a high density in Fig. 13 that its exciting current consisted mostly of harmonics, and these through armature reaction produced initial distortion in the flux, and therefore the voltage wave. In Fig. 12, because of the lower generator voltage, the transformer iron was operating at half the former density, and therefore the exciting current must have been more nearly sinusoidal, and much less in magnitude.

E. E. F. Creighton: Do I understand that these oscillograms were taken with that machine designed by Prof. Adams?

C. L. Dawes: No, these were taken from the original generator. This has been superseded by the machine designed by Prof. Adams. I have no oscillograms of the new generator with me.

E. E. F. Creighton: I think that is an important point. You see the machine has teeth in it, and I am wondering whether you are not getting exactly the same thing with different capacities. I have not been able to get rid of the tooth harmonics, and the only way we can get rid of these harmonics is by making the core smooth, smooth iron surface all the way through, and it seems to me anything in the form of a practical generator would always give these ripples, if the capacity and the inductance were of the proper value to magnify them. These currents would carry back into the generator and react in the armature and still further magnify the effects.

C. L. Dawes: The tooth harmonics of an alternator may be reduced to an almost negligible quantity by making the number of slots per pole per phase a non-integer. This produces a Vernier effect. For instance, the effect of one and a quarter slots per pole per phase has the same effect upon the wave form as five slots per pole per phase. At Cambridge under Prof. Adams's direction we have wound induction motor rotors with a distributed field winding, and used the motor as an alternator. Even with this very short air gap, the tooth harmonics have been made almost negligible, due to the fact that the ratio of rotor to stator teeth was so chosen as to produce a Vernier effect.

E. E. F. Creighton: Did you try to resonate?

C. L. Dawes: We did not attempt to resonate, but connected a condenser load to the machine and looked for harmonics in the current wave.

Comfort A. Adams: I do not wish to appear to claim that it is a perfectly easy matter to design commercial alternators that will eliminate all possibility of resonance, as suggested by Prof. Creighton. But I do think that this possibility can be reduced to such a degree of remoteness that it need not be considered, and this too in a machine costing only a little more than a standard alternator of the same rating. I wish also to point out again that in the case of a full capacity load, the reactance of transformer and alternator will absorb all the high harmonics, and that a moderate amount of additional series inductive-reactance will insure a substantial sine wave of terminal voltage with almost any alternator. The danger comes with small capacity loads.

L. W. Chubb: I have noted several cases of resonance of multiple frequencies in circuits in which there was only a load or voltage change. The effective inductance of iron cores decreases with increased saturation and in some cases the presence of small high-frequency components of voltage will cause destructive resonant disturbances. In one case I have in mind the resonance of a fifth-harmonic voltage across the terminals of a testing transformer at a certain excitation would rise to over 400,000 volts by a spark gap, while the ratio would indicate less than 200,000. The ratio just above and below this point would be approximately correct and the fifth-harmonic voltage almost unnoticeable.

John B. Whitehead: The net result of the discussion has indicated, it appears to me, that there is certainly not any one of these factors to which we can turn in meeting the troubles caused by irregular wave form. But it is interesting to note that the discussion has finally taken the turn of suggesting that it may be possible, after all, to obtain a reasonably pure sine wave. Within the last few months I have been attempting to get a small generator, 50 kv-a. with a pure wave, and I think I shall succeed. In discussing this particular generator the designing engineers of one of the large manufacturers have given me considerable information, and I hope that Mr. Foster, with whom I have discussed this generator quite recently, will say something about a large generator, the curves for which he has shown me within the last few days, as bearing on the question of capacity and its relation to wave form. Possibly he may not wish to say anything, but it was so interesting that I hope he will tell this audience what he was willing to tell me.

William J. Foster: Before speaking directly on the point brought up by Dr. Whitehead, I wish to say that during the last five years very decided improvements have been made in the design of generators in the matter of potential wave for all conditions of load. At the same time this improvement has been going on, the natural development and progress in transmission work has assisted in the no-load condition, for the reason that the large waterwheel and steam turbine generators are of so great capacity that they have very large air-gaps, in comparison with the breadth of the slots, which tend to minimize the harmonics. Most decided improvements have been made in certain little details of construction which tend to eliminate the effect of the slot. It is possible to produce an effect equivalent to a machine of a very large number of slots per pole.

To illustrate, suppose we have a machine that is designed for forty-two poles with one slot per phase per pole, but it is connected up for forty poles—we then have the effect of twenty-one times the number of slots, or sixty-three slots per pole, which, for 60 cycles, carries us beyond what has been pointed out in this long message that we have from the Pacific Coast as the upper limit of telephone interference.

The particular machine that Dr. Whitehead has referred to is a large waterwheel-driven generator, with small number of slots, running at very low speed, which has the Vernier idea introduced into it, the same as in the case of some other recent machines. But what concerns us now is the establishment of some standard by which to test the wave, and I had hoped from Dr. Bedell's work and these papers and the discussion that we might arrive at some conclusion. As far as I am personally concerned, I know of nothing better than the measurement of the deviation from a true sine. It was nearly twenty years ago, in connection with an installation abroad, that we were asked to draw up some clauses for the specifications. At that time we had no oscillograms or wave meters, and the potential waves were determined by the contact, instantaneous method, and plotted. It was then customary to plot in rectangular co-ordinates, but the clause that was drawn up for these specifications was on the basis of plotting in polar co-ordinates, and determining the percentage on the radii intersecting the equivalent circle. I still think that the deviation from a true sine—if we could a rrive at something that would be fair, which would be possibly 3 per cent at no-load, 5 per cent at 100 per cent power factor full load, and 7 per cent at 80 per cent power factor—at the present time is, perhaps, about all we are ready for, unless these gentlemen, from the theoretical standpoint, can suggest some instrument by which we can measure the harmonic factor or curve factor, or a combination of the differential and integral distortion factors, so that we will be able to catch the harmonics which are causing the greatest trouble.

The machines which have been referred to here by Dr. Adams and Dr. Whitehead are machines which have been built with reference to a good wave form under different conditions of load, and consequently they can hardly be considered as commercial machines. Although the air gap is small in some of them, the armature reaction is low, consequently they are costly machines. They are built with reference to minimizing the effect of armature reaction, whereas the tendency has been towards very large generators in commercial work that require high armature reactions and consequently heavy distortions under load conditions. Another reason for such machines is that they are better, far better for general use, in that they are more immune from line troubles, etc., the instantaneous short circuits being reduced to a low value. Consequently, if rigid requirements are made for all conditions of load, as has been proposed, it will mean more costly machines and also, as far as I can see, must limit the capacity of the machines. As we are contemplating 50,000-kw.

generators, and even larger, it is quite a problem to face the situation brought about by what is asked or suggested by the telephone companies.

Frederick Bedell: The points raised by Mr. Chubb and others in regard to form factor are without doubt technically correct, although they do not affect materially the general character of the conclusions. They do, however, affect some of the numerical results, particularly in extreme cases. The results given in the paper were obtained by integration from the zero of the fundamental wave, which makes solution possible, and not from a zero of the total wave (as strictly they should be), which would make the solution extremely difficult if not impossible in many cases.

Mr. Lyon, as well as Messrs. Chubb and Adams, has shown* that even for the particular study of hysteresis loss, the use of form factor is not exact in extreme cases, although exact enough in most practical cases. All agree with the conclusion of the paper that, aside from the study of hysteresis loss, form factor is meaningless as an indication of wave distortion.

Mr. Chubb has told us of his early use of the differential distortion factor as a measure of wave distortion. Its use in a-c. equations was, however, previous to this, being developed by B. Arakawa† under the direction of the writer in 1908-1909.

Messrs. Middleton and Dawes have most interestingly brought out the important effect of wave distortion in connection with cable testing and have emphasized the desirability of having the least possible distortion for such testing.

The Committee on Inductive Interference in their message from San Francisco likewise point out the great effects of higher harmonics in telephone disturbance and suggest penalizing the higher harmonics even more than is done by the differential distortion factor δ. Dr. Osborne has given additional data bearing on this. To weight the several harmonics up to a certain frequency in an arbitrary manner would, however, have the disadvantage that the result would be arbitrary or empirical, incapable of direct measurement (unless one invents an intelligibility meter), and incapable of use in analytical equations. If δ or some function of δ could serve their purpose for practical purposes, it would have the advantage of general applicability, not limited to this one case only. Still, a special interference factor may be necessary.

Mr. Lyon concludes that the well-known method of solution in which harmonic components are calculated separately is

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*This is shown by M. G. Lloyd, "Effect of Wave Form upon the Iron Losses in Transformers," *Bul. Bureau of Standards*, Vol. IV., p. 477, 1908.

†See "Vector Representation of Non-Harmonic Alternating Current," *Physical Review*, p. 409, Nov. 1909. The correction factor ρ there used (p. 424) is the distortion factor δ.

superior in the completeness and accuracy of the results. No one will disagree with this, but such a method of solution assumes that we have available *the complete wave form* and its analysis. At times we wish to handle such problems *without* these data, either through choice or necessity, and it is for this purpose that these papers have been prepared. The method of separate harmonic components and the method of these papers, are not rival or alternative. Furthermore, it is to be kept in mind that the method of separate harmonic components, as well as the method of these papers, unless modified can be applied with accuracy only when R, L and C are constant, and so has no advantage in this respect. The assumption of constant R, L and C is, however, a close working approximation in many cases, even when it is not exact. Solutions have been published* for certain special cases in which R, L and C are not constant.

When a quarter of a century ago analytical and graphical methods, based on the assumption of a sine e. m. f. and constant R, L and C, were being evolved—such methods for example as are given in Bedell and Crehore's "Alternating Currents"—the criticism was commonly heard that such treatment was academic and useful only for the theorist, for the reason that alternating currents in practise were not true sine waves and R, L and C were not constant, so that the results could not be of practical value. But this criticism soon wore away, and every engineer has used with success methods based on these assumptions for calculating transmission line regulation, the behavior of a transformer or induction motor by the circle diagram, or some similar problem. So won over to the sine-wave assumption is the practical engineer that, not uncommonly, he now stands on the other side of the fence and says of harmonics that they may possibly exist, but that *their* study is academic and only for the theorist. Harmonics, however, do exist, and while in many cases they may be neglected, there are other cases, as has been brought out in this discussion, in which their effect is important; it is for these cases that these papers have been prepared.

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*"The Effect of Iron in Distorting Alternating-Current Wave Form," by F. Bedell and E. B. Tuttle, TRANS. A. I. E. E., XXV, p. 671, 1906. "Distortion of Alternating-Current Wave Caused by Cyclic Variation of Resistance," by F. Bedell and E. C. Mayer, p. 333, this volume.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

I—Notes on Investigation of Types of Foundations—Digging Holes for Foundations—Concreting Foundations—Erecting Towers

BY J. A. WALLS

ABSTRACT OF PAPER

Concrete tower foundations of mushroom type, requiring no forms or back filling, as used in recent Baltimore-Holtwood transmission line, are found to be cheaper and stronger than steel tripod foundations previously used in a similar line alongside.

It was found that mushroom type concrete foundations could be built with a smaller construction force and at lower cost, and more rapidly, than certain types of concrete foundations requiring forms and back filling.

The procedure of digging holes and concreting of mushroom type foundations is described.

Method of erecting transmission towers by the use of a shear leg is described in some detail.

THE FOLLOWING notes relate to the transmission lines of the Pennsylvania Water & Power Company. On the first Holtwood-Baltimore Line (No. 12) the steel tripod stub, Fig. 1 was used with suspension towers and a concrete foundation, Fig. 2, with anchor towers.

On the Holtwood-Lancaster Line mushroom type concrete foundations were used for both suspension and anchor towers.

Lifting tests made on steel tripod stubs, steel single-leg stubs (with fins at top and bottom, Fig. 4) and under-cut mushroom type concrete stubs (the lift being not vertical but inclined, and parallel to the direction of the tower leg, though in service the horizontal component would be somewhat greater than this) showed that the tripod type pulled out of fresh ground at about 32,000 pounds; the single leg at about 23,000 pounds; while the mushroom concrete type showed no signs of lifting or cracking of soil up to the limit of capacity of the testing outfit, *i. e.*, 70,000 pounds. The shifting of the single leg stub was more than one inch at 50 per cent of its ultimate loading; the tripod stub movement at 50 per cent ultimate loading was $\frac{1}{4}$ in. in the vertical direction and $\frac{5}{16}$ in. in the lateral direction.

Experience in the field indicated greater difficulty in securing exact setting with the tripod stub than with the concrete stub, so in view of the greater strength of the concrete stub, its lesser liability to displacement when pivoting on it in tower raising, and the consequent lessened chance of unequal stressing of the tower legs, due to lack of fit of the tower shoes with the foundations, together with certain other construction advantages, determined the use of concrete stubs for both suspension and anchor towers on the second Holtwood-Baltimore Line (No. 56). The reason for the massive construction adopted, it should be explained, is that this latter line is a short and important trunk line

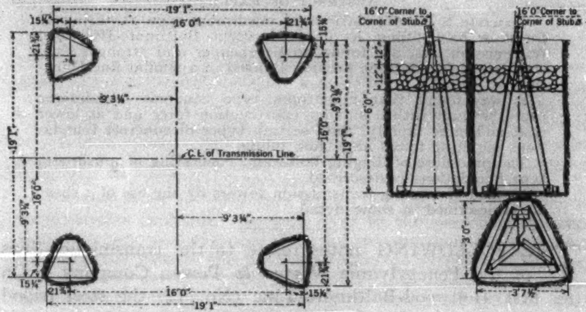


FIG. 1—STEEL TRIPOD TYPE FOUNDATION

of very heavy construction, *i. e.,* 15,000 pounds and 30,000 pounds breast pulls for suspension and anchor towers respectively carrying two circuits of 30,000 kw. per circuit and insulated for 110,000 volts.

Investigations were made on four types of concrete foundations to determine which type of foundation would best suit our conditions. Concreting was done with a hand mixer. The earth was hard red clay with a few small boulders.

The mushroom type, without forms, was constructed by digging a post hole, approximately 16 in. in diameter, 6 ft. in the ground and under-cut at the bottom of the hole as shown in Fig. 3. It was later found advisable to dig the post holes only 3 to 4 ft. deep and make a bell shaped expansion in the bottom by the use of dynamite. The mushroom type, in good ground, is cheaper to build, can be built more quickly than the other types experimented with, and is especially satisfactory on account of not disturbing the adjacent ground or necessitating backfill.

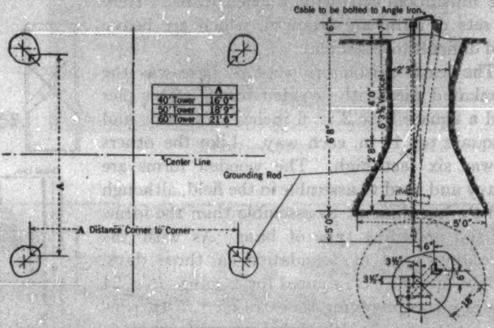

Cable to be bolted to Angle Iron
A
40' Tower 16'0"
50' Tower 18'9"
60' Tower 21'6"
Center Line
Grounding Rod
A Distance Corner to Corner
A
6"
2'3"
4'0"
6'3½" Vertical
6'8"
2'8"
5'0"
5'0"
6"
3½"
3½"
6"
15"

FIG. 2—MUSHROOM TYPE CONCRETE FOUNDATION FOR HEAVY TOWERS

The next best type of foundation appeared to be the mushroom type using steel forms. Considerable difficulty was experienced at the start with the latter type owing to the difficulty

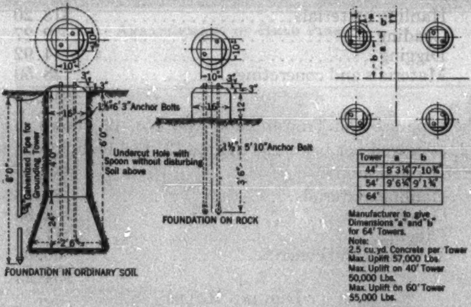

10"
10"
10"
10"
3"
3"
3"
3"
16"
16"
12"
1¼"×6' 3" Anchor Bolts
Undercut Hole with Spoon without disturbing Soil above
1½"×5' 10" Anchor Bolt
Galvanized Pipe for Grounding Tower
8'0"
4'0"
6'0"
24"
2'6"
3'6"
FOUNDATION IN ORDINARY SOIL
FOUNDATION ON ROCK
a
b
b
a
Tower a b
44' 8'3¼" 7'10⅝"
54' 9'6¼" 9'1⅝"
64'
Manufacturer to give Dimensions "a" and "b" for 64' Towers.
Note:
2.5 cu. yd. Concrete per Tower
Max. Uplift 57,000 Lbs.
Max. Uplift on 40' Tower 50,000 Lbs.
Max. Uplift on 60' Tower 55,000 Lbs.

FIG. 3—MUSHROOM TYPE CONCRETE FOUNDATION

of keeping the forms properly lined up and vertical, since the form had a tendency to float and cant when the concrete was poured into it. It was found possible to prevent this by backfilling slightly before pouring the concrete, the backfilling not being too much to prevent the withdrawal of the steel forms. In this type and the following types, excavating by dynamite did not prove successful.

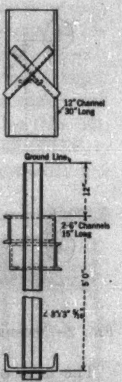


Fig. 4—Steel Single Leg Stub

Next in order in point of cost and rapidity of construction was the mushroom type with wooden forms. Here 24 sets of forms are required, which are heavy and difficult to assemble.

The least satisfactory type of base was the trunkated pier with wooden forms. This pier had a square base 2 ft. 6 inches each way and a square top 12 in. each way. Like the others it was six feet high. The wooden forms are heavy and hard to assemble in the field, although a little less difficult to assemble than the forms for the preceding type of base. As with the preceding type of foundation, a three days' supply of forms is required for a gang, *i. e.* 24 sets of forms involving, as extra men, a carpenter, a foreman, and three helpers with team to provide steady work for the concrete gang.

The type adopted on Transmission Line No. 56 was that shown in Fig. 3 and the actual cost of this type on the line averaged per tower, as follows:

Hauling materials	$13.20
Grading	2.27
Digging	4.92
Materials and concreting	28.50
	$48.89

The type used on Transmission Line No. 12, shown in Figs. 1 and 2, averaged per tower, as follows (3 steel foundations to one concrete foundation):

Hauling materials	$8.03
Grading	4.80
Digging	11.34
Materials and concrete	30.08
	$54.25

DIGGING HOLES

Tools. Each man in the digging gang is provided with the following tools:

1 Long handle shovel,
1 Digging spoon with 8 ft. handle,
1 one inch by 8 ft. telegraph digging bar,
1 Post hole digging bar 6 ft.

PLATE LIII.
A. I. E. E.
VOL. XXXIV, 1915

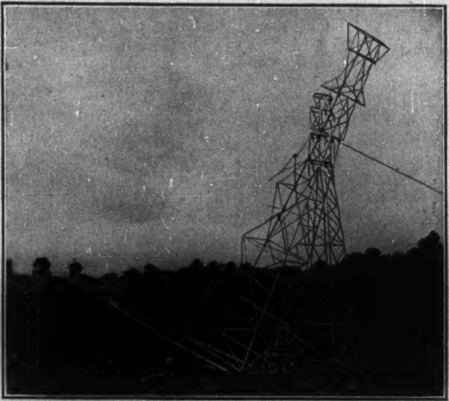
Erecting shoe

ERECTING SHOE [WALLS]

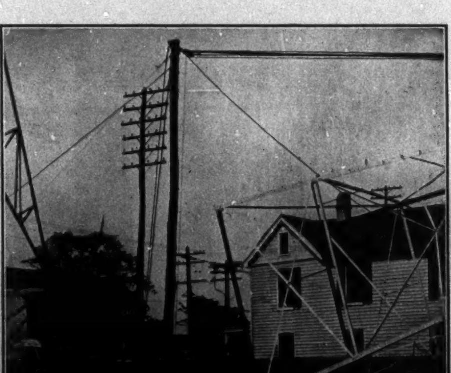
ARRANGEMENT OF HEAD PINS [WALLS]

SIDE GUY TACKLE [WALLS]

PLATE LIV.
A. I. E. E.
VOL. XXXIV, 1915



BACK GUY TAKING WEIGHT [WALLS]

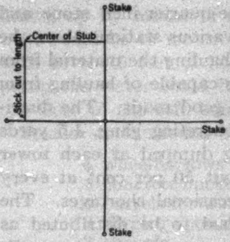


ERECTING TOWER WITH GIN POLE RIG [WALLS]

The foreman is provided with 40 per cent dynamite, exploders and battery.

The foreman lays out and stakes the center of each hole. In order to avoid the transportation of a templet, the laying out is done as follows:

The engineer stakes the center of the tower and marks the tower height on the reference stake; in addition to this two stakes are put down in the direction of the line and two stakes across the line. These four stakes give the center line of the base. A cord is strung across two of the stakes and the distance from the center stake to a line through the center of two holes on the same side measured by means of a stick cut to length. The point arrived to is marked with a pin and the operation is repeated on the other side of the center. By swinging the cord 90 degrees to the other stakes two more points are located. By laying out two sticks of a length equal to half the base width of the tower from two adjacent points found in the first operation, and then swinging them till their ends meet, the center of one corner is located. The operation is best understood from the accompanying sketch.



In this way two men can lay the base out in less than five minutes and no heavy tools are required. One man is provided for each hole, and the foreman is able to take care of three to four gangs. When a man starts a new hole he first makes a circle, approximately 16 in. diam. around the pin, and the foreman sees to it that he keeps his hole inside this circle.

The hole is dug about three feet deep, using the post hole bars to loosen up the soil, and a long handle shovel to scoop it out. If the soil at this depth is too hard to scoop out with a spoon a hole about two feet deep is punched in the center and the hole shot with about one half stick of dynamite. The dynamite will loosen up the soil and works down and sideways so as to form the bell. After the shooting, the loose dirt is scooped out with a spoon. Under ordinary conditions one man can dig from two to three holes a day in this manner. In some places rock has been encountered. Sometimes this rock is soft enough to be dug out with a bar, in other places it has to be drilled and dynamited. Three to four shots generally opens the hole. It has been tried to blow holes open with dynamite in the following way:

A hole is punched about four feet deep by means of a bull point and one half stick of 60 per cent dynamite lowered to the bottom of the hole. One half stick of 40 per cent dynamite is suspended in the hole about 8 inches above the bottom stick and another half stick of 40 per cent with a fuse cap about 20 inches from the top. By this method one man has been able to open a hole in 45 minutes, but due to unfavorable soil encountered, this method was not generally followed.

CONCRETING

The concrete mixture used for the foundations is made in proportions varying from 1:2:4 to 1:3:5. The cement is good quality Portland cement. Test samples taken from various lots show that the cements meet the specifications of the American Society for Testing Materials. Three-quarter-inch stone and sand were shipped in carload lots to various stations along the line. Four head teams were used for hauling the material from the railroad stations, each team being capable of hauling from ¾ yard on bad roads to 1.5 yards on good roads. The distribution was kept well ahead of the concreting gang, 1.5 yards of stone and 3.4 yards of sand being dumped at each tower site. This amount was increased about 50 per cent at every fifth tower, so as to make up for occasional shortages. The cement was delivered in bags, and had to be distributed as the work proceeded. In most cases no storage room was available at the railroad stations and, therefore, the cement had to be stored in farmer's barns along the line, 100 to 200 bags being stored at each place. A team following the concreting gang could pick up the cement at these barns and could distribute the bags directly ahead of the work. This procedure kept the loss due to wet weather at a minimum.

The equipment for a gang of men engaged in transmission line work must necessarily be made as light as possible on account of the small amount of work to be done at each place. This is especially true of the concreting gang, as those men invariably spend more time in moving than in concreting.

The time required for mixing and pouring the concrete is about three quarters of an hour, while moving and setting up takes about one hour. The move from tower No. 312 to No. 313 at Big Gun Powder crossing may be given as an exaggerated example of the time required for moving. The teams had to make a detour of about five miles at this place and it required eight hours to move the concreting outfit between the two towers, a distance of 1100 feet.

A 2.5-cu. ft. hand mixer had done excellent work on the Lancaster transmission line and such a mixer was, therefore, purchased for the work on line No. 56. This mixer runs on two wheels and weighs about 1000 lb. with loading platform. The wheels are provided with separate axles and a few days work showed the necessity of strengthening these axles, which was done with a heavy flatiron strap on each side of the mixer. This mixer is still in good condition after being hauled 40 miles over rough ground. Water was hauled in a steel tank mounted on a two horse wagon. The tank was made of ½-in. steel plate, which proved to be unnecessarily heavy.

Water was taken from small streams and creeks and was drawn up by means of a 4-in. boat pump. A more efficient way would be to mount a small lever suction pump equipped with 10 to 15 feet of hose on the tank wagon. With such a pump the water could be reached without driving the wagon too close to the soft banks of the stream.

Smaller tools needed by the concreting gang are:

4 wheelbarrows
4 concrete buckets
4 barrels for water
2 digging spoons
3 shovels
1 digging bar
1 concrete chute for the mixer
1 level board
1 24-in. carpenters level
1 cross-cut saw
1 maul hammer
1 set of carpenters tools

In addition to this, a small amount of blocking and running boards must be carried.

The smallest number of men needed for efficient handling of this work is one foreman with nine men, with from one to three teams, depending on the length of haul of water and cement. The men would be distributed as follows:

One man wheeling stone
" " " sand
Two men wheeling concrete

One man hauling water and cement
Two men turning mixer
One man loading wheelbarrow with concrete
One man tamping
The teams hauling water, cement and assisting in moving.

Two or three additional men can and have been used to advantage in this gang. When placing concrete these additional men seem unnecessary being mostly occupied with loading sand and stone in wheel-barrows and bailing water from one barrel to another, this latter operation being necessary on account of the difficulty in moving the water wagon or a full barrel. The real benefit of these men is, however, shown when moving. Let us consider a case where two teams are available for moving. As soon as the last batch of concrete is mixed a number of men will start loading the tools on the wagon. But before this, two men have been sent ahead to set the forms and place supports for the templet. Ten men are needed to move the templet and this leaves one man in a gang of thirteen to help the teamsters clean up the place and unload at the next tower. At the new set up the foreman will use four men or five men in lining up the templet. One man handles the level board and four men move and block up the templet in position and then place the anchor bolts. In the meantime the other men have completed the unloading, blocked up the mixer to such a height to permit a wheelbarrow to be placed under the chute and laid out the running board so as to make everything ready for the placing of concrete.

With only one team available, two trips must be made for the tools, and with a smaller number of men, one part of the job must wait for the other. It is, however, to be noted that the records do not show any saving in money, but the speed is increased. Naturally the larger gang will make a better showing in rough country where the moving is hard, than on a level stretch with good going. Two men and a team were sent back occasionally to strip forms, bringing them ahead, distributing them where needed.

Originally buckets were used for removing the concrete from the mixer, but this proved to be inefficient as concrete could be mixed faster than it could be removed. A portable inclined runway was, therefore, made by means of which the mixer could be elevated enough to permit the placing of a wheelbarrow under the chute. When water was found in the holes it was removed with a boat pump. This worked all right in such places where the holes filled slowly, but in a few instances the water would fill in very fast and the holes could not be kept dry. It would be well to carry a short length of six-in. sheet iron pipe for such cases. The concrete could then be poured through the pipe without draining the holes and there would be no chance for the water to wash the cement out of the mixture. At the last end of the job a broken boat pump was used for this.

No bed plates were on the job when the work was started, and it was, therefore, tried to finish the first group of piers with help of dummy plates. This proved to be a very slow process and did not provide a very good seat for the plates. The dummies were then abandoned and until the plates arrived, piers were left about eight inches below the final grade. As soon as the plates arrived, an instrument man with his rod man and one laborer were sent back to finish the foundations, the bond between new and old concrete being obtained by means of toxement.

When bedplates are on hand at time of making the piers, the concrete is poured to within an inch of the top of the bolts and the instrument man gets his grade by hammering the plates down in the soft concrete, and is relieved from carrying cement and mixing concrete.

All material used for concreting during cold weather was heated, the piers were built up to ground line only and covered with sand to prevent freezing. When warm weather arrived men were sent back to finish these piers.

ERECTING TOWERS

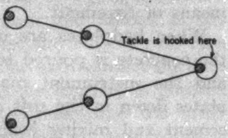
Whenever possible the towers are assembled on the ground in a horizontal position. A rigging gang follows the assemblers and erects the towers. This rigging gang consists of a foreman with 11 men and a four-head mule team. The general scheme of erection is to pivot the lower tower legs to the foundations and then lift the head of the tower by means of a tackle running from a point below the cross arms over a shear leg to a dead end at a convenient distance ahead of the tower. The lifting is done by hitching the mule team to the lead line.

Dead Ends. In average soil the dead end consists of heavy iron pins, 2.5 in. diam., about 5 ft. long. Five of these pins are used for the main tackle, three for the back guy, and one for the side guy. The pins are driven about three feet apart and connected with a chain, as shown in the accompanying sketch. The tackle is hooked in the front edge of the wedge.

Tackle. The main tackle consists of two 12 in. three-sheave blocks reeved with 600 ft. of 1.25-in. hemp rope. Both the side and the back guy tackles consist of 8-in. two-sheave blocks reeved with ¾-in. rope. The side guy tackle need only be a short one, but the back guy tackle is of the same length as the main, so as to reach out to the shear leg.

Shear Leg. The shear leg is made of two 45-ft. spruce timbers, measuring about six in. at the top. The height of the lift is less than 43 feet as the timbers are bolted two feet from the top and the butts are spread about 16 feet. The pole tops are shod on both sides with heavy steel plates, so as to prevent splitting. The butts are grooved for kick lines.

Pivots. The light section 40-ft. towers are pivoted on a ⅝-in. case hardened machine bolt on each side, the bolts running through the leg angle and standard foundation shoe. One tower was dropped and slightly damaged on account of a faulty foundation shoe breaking. This led to the ordering of one pair of shoes made of extra heavy angles and of such a height that the tower leg cleared the foundation plate by more than ½ in., while the tower was being raised.



All extension and heavy towers are bolted to a hinge turning on a 1.25-in. bolt. The hinge and bolt are supported by means of a ¾-in. plate bent in channel shape with the web resting on the foundation.

Setting up Rigging. Two men each at the main lift and back guy select a spot in line with the tower and drive their pins for the dead ends. Twenty pounds sledge hammers are used for driving the pins. If the ground is too soft to hold the pins, a dead man is buried. One man rigs up the side guy, two men put the shear leg in place, fix the kick lines and fit the shoes on the tower, while two more men put spreaders between the tower legs and attach the chains for the lifting tackle and a sling for the back guy. The main lift is hooked to the corner angles at the point where the braces in the first and second panel below the cross arm meet. This brings almost the full weight of the tower on the tackle. It was found unnecessary to use any spreaders in the chains. The spreaders used in the tower legs consist of two by four-inch green oak bolted together so as to form four by four-inch. Two pieces bolted together make a more elastic strut, less liable to break if it falls down.

Lifting Shear Leg. With pins driven, shoes fitted, and the shear leg in place, everything is ready to lift the shear leg. A wooden cross piece, usually four by four inches, is placed over the upper tower legs so as to give the shear leg a start. The back guy tackle is hooked to a wire cable, running over the cross piece to the top of the shear leg and a pair of mules in the lead line lift the shear leg with main tackle and all. The main tackle is used for steadying the rig as the lifting cable is made to such a length that the shear leg must be pulled a little ahead before the chains can be hooked. The block of the main tackle is placed right at the top of the poles. As soon as the chains are hooked the tackle is slacked back and unhooked. The wire cable used for this lift is then lashed to the tower, so as to prevent the shear leg from falling when the main tackle lets go. Lifting the shear leg this way, besides being the most convenient method, gives a good test on the pins in the back guy.

Hoisting Tower. The shear leg being up and all rigging in place, the four-head mule team is hitched to the main lead line. Two men are stationed at each set of pins and no strain is taken before these men have reported everything o. k. On the first start the team goes just far enough to put full stress on the pins, and then stops. If everything proves all right, the team is ordered ahead and proceeds slowly until the men at the back guy commence to feel the weight of the tower on their tackle, when the team is stopped. This is the most critical point of the erection, as the tackles on both sides of the tower must be kept taut. In case of a line fouling, one step too far by the team is liable to pull the pins out or break a tackle, and the tower will fall. The team is, therefore, moved a step at a time only, at this stage, until the weight of the shear leg is sufficient to pull the tower over, when the team is unhitched and the tower let down with the back guy alone. The front leg being about six inches from the foundation, the tower is held until the spreaders are moved and one foundation shoe fitted to each side. When the tower is lowered the remaining six inches, these shoes are guided over the foundation bolts. In case the special erecting shoe is used the tower is rocked ahead by means of the main tackle and these shoes exchanged for standard ones.

The side guy is used for emergency only, and is kept taut enough to take out the slack while the tower is going up, but it is not allowed to take any stress. In case something breaks this guy prevents the tower from falling onto line No. 12.

Moving. As soon as the main tackle is unhooked it is stretched by the team so as to be ready for the next lift. The tackle being stretched, a chain is slung around the shear leg and the team drags it to the next tower. In the meantime, the respective men coil up their tackles and load them on a wagon, together with pins, hammers, spreaders, and the like. While this is being done, one man has put all the foundation shoes on the tower with one bolt in each shoe. The final bolting up of these shoes is done by two men behind the rigging gang and counted as members of the same crew.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

II—TRANSMISSION TOWER STEEL ANCHORS SET IN EARTH

BY J. B. LEEPER

ABSTRACT OF PAPER

As tower anchors have been somewhat overlooked, causing in some instances much loss, these notes are written to call attention to the importance of properly designing them so that the maximum strength of tower may be obtained with the most economical outlay. The notes show:

1. A method of figuring the loads to be resisted by the anchors.
2. The importance of resisting the horizontal as well as the vertical loads.
3. The effect of the shape of the anchor on strength of tower.
4. Various types commonly used.
5. The economy of the use of an all-steel anchor.

THE ABILITY of a tower to resist the loads coming on it depends largely on properly designed anchors and it is the intent of the following notes to call attention to this fact.

A large percentage of the loads on a tower or pole, are in a horizontal direction, and are applied thereto near the top, causing an effect of overturning at the base. This overturning moment, together with the load causing it, must be taken up by the anchorage.

To illustrate; let Figs. 1, 2 and 3 represent wide base towers having separate anchors for each leg. Fig. 1 illustrates a tower in which the leg angles extended would intersect at or near the resultant of the applied loads. Fig. 2 represents a tower with parallel legs where the bracing carries all the horizontal loads, while, Fig. 3 shows a tower with legs battered so that part of the horizontal forces are carried down through the legs and part by the bracing.

Let A represent a horizontal force applied to the tower at height X from the base, then the anchors must resist a horizontal force equal to A, and a moment equal to AX. If Y equals the distance apart of anchors, then $\frac{AX}{Y} = B$, or the vertical load on each anchor due to force *A*, force *B* acting downward on one anchor and upward on the other; the horizontal force *A* being divided equally between the two anchors if the tower is built as shown in Fig. 1. If built as shown in Fig. 2, it is all taken up by the tension anchor, while if built as shown in Fig. 3, the tension anchor takes the same amount as the compression anchor plus the shear carried down by brace *Z*. If horizontal strut *W* is used on towers of Figs. 2 and 3 the anchors will each carry one-half of load *A*, as for Fig. 1.

In designing the anchors both the horizontal and vertical loads must be kept in mind, and as illustrated above, the position of the loads, together with the shape of the tower, will determine the amount of each.

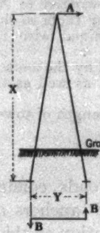


FIG. 1

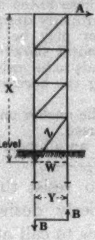


FIG. 2

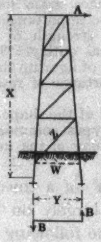


FIG. 3

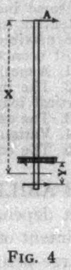


FIG. 4

To resist the vertical load on the anchor is a comparatively easy matter and is usually done by extending the leg of the tower down into the ground to a steel or concrete base.

On account of the variability of the character of the earth and the uniformity of the material in the towers, it seems that the anchors should be designed for a greater possible overload than the towers. How much greater is a question of judgment only.

In designing the anchors to take the uplift we assume the weight of earth at 100 lb. per cu. ft. and that of concrete at 150 lb. In case of an all-steel anchor we figure the weight of an inverted frustum of a pyramid whose sides incline at an angle of 30 deg. with the vertical, assuming this to be the ultimate resistance of the anchor. From the results of some of our tests it seems that these assumptions will give no allowable overload with freshly tamped earth (see report of tests appended). We have made no tests on anchors after they have

REPORT OF TESTS ON STEEL ANCHORS

Showing Movement Due to Loads Applied to Towers

Test No.	Dist. A	Base	Uplift Thou. lb.	Comp Thou. lb.	Vert. Move't. inches		Horz. Move't Top of Stub		Time set before Test	
					Up-ward	Down-ward	Ten-sion	Comp.		
1	7′ 6″	30″ Sqr.	24.8	24.8	1.44	.31				"A" frame bolts failed in conn. of stub to leg. 4-23-13
			37.2	37.2	4.00	.56				
			49.6	49.6	7.00	1.06				
			64.6	64.6	7.25	....			5 mo.	
2	7′ 6″	30″ Sqr.	24.8	24.8	.37	1.00				"A" frame comp. stub buckled 5-15-13
			37.2	37.2	1.13	1.63				
			49.6	49.6	3.00	2.50			2 mo.	
			53.4	53.4	....	....				
3	6′ 0″	10″ × 30″	7.4	7.4	.25	.25				"A" frame anchor pulled up. 4-23-13
			14.9	14.9	1.87	.75				
			19.3	19.3	....	....			3 mo.	
4	7′ 6″	30″ Sqr.	5.7	15.7	.06	.44				Tower A Tower failed in lower panel due to movement of anchors horz. and vertical. 7-1-13
			11.1	21.1	.56	.44				
			16.5	26.5	1.31	.81	Not R	ecorde	d	
			21.9	31.9	2.31	1.00			6 wk.	
			26.6	36.6	4.06	1.19				
			42.0	52.0	....	....				
5	7′ 0″	30″ Sqr.	1.60		.31	.31				Tower A 1. Tower failed by shear of bolts about halfway up the tower. 9-15-13
			31.2		.75	.94				
			36.6		....	1.06				
6	10′ 0″	60″ × 72″	40.0	45.6	.13	.06				Tower B. Tower failed in lower bay due to movement of anchors. 10-14-13
			60.9	67.5	1.06	.25				
			81.9	89.3	2.62	.50	+1.25	−.44	—	
			102.8	111.2	4.69	.75	....			
			107.7	116.3	5.56	....	+3.00			
7	10′ 0″	60″ × 72″	39.1	46.9	.13	.13				Tower B. Tower failed in bottom bay. 12-12-13
			60.7	68.5	.31	.31	+ .25	−.13		
			82.2	90.0	.56	.44			12 da.	
			103.7	111.5	.87	.62				
			121.6	129.4	1.13	.69	+ .50	−.50		
			135.4	143.2	....	....				
8	10′ 0″	60″ × 72″	39.1	46.9	.13	.19				Tower B Tower not tested to destruction. 12-22-13
			60.7	68.5	.37	.25	+ .25	−.13		
			82.2	90.0	.62	.37			4 wk.	
			103.7	111.5	.94	.50				
			121.6	129.4	1.25	.62	+ .75	−.13		
			136.8	144.6	1.50	.69				
9	9′ 0″	48″ × 60″	41.2	45.2	.31	.25	+ .25	− .0		Tower C. Tower leg failed in lower panel 12-5-13
			56.4	60.4	.50	.44				
			80.0	84.0	1.00	.75			3 wk.	
			100.0	104.6	1.87	.94				
			112.7	116.7	....	....				
10	7′ 6″	30″ Sqr.	31.0	36.0	.62	.50	+ .25	.0		Tower C. Tower leg failed in lower panel. 7-16-14
			36.0	41.0	1.00	.81	+ .25	.0	2 wk.	
			40.0	45.0	1.19	1.00	+ .37	.0		
11	7′ 0″	30″ Sqr.	26.3	29.7	.44	.50	+ .13	.0		Tower E. Tower failed near top. 8-28-14
			34.1	37.5	.75	.75	+ .13	.0	2 da.	
			41.0	44.5	....	....				

Tests 1, 2 and 3 were made with "A" Frames.
Tests 4 to 11 inclusive were made with 4 legged Towers.
Style of anchor for tests 1 to 4 incl. and 5 to 9 incl. similar to Fig. 9.
Style of anchor for tests 5, 10 and 11 similar to Fig. 8.
Bases of all anchors were in form of grillage except No. 3 which was $2L^s$ *b* to *b*.
Distance A above is depth of grillage from ground level.

been set long enough for the earth to have settled in the hole and become bonded with the surrounding earth. The tests we have made show that the earth in the hole moves up without disturbing the surrounding earth. It would be very interesting to test some anchors for the uplift after all settlement has been completed, although a transmission line is usually in operation long before the earth has settled completely.

We have found that, although the load on the anchor of the compression side is somewhat greater than the uplift, the governing feature is the uplift, and that if the latter is properly cared for there will be practically no movement downward on the compression side, the anchors for each leg being made alike.

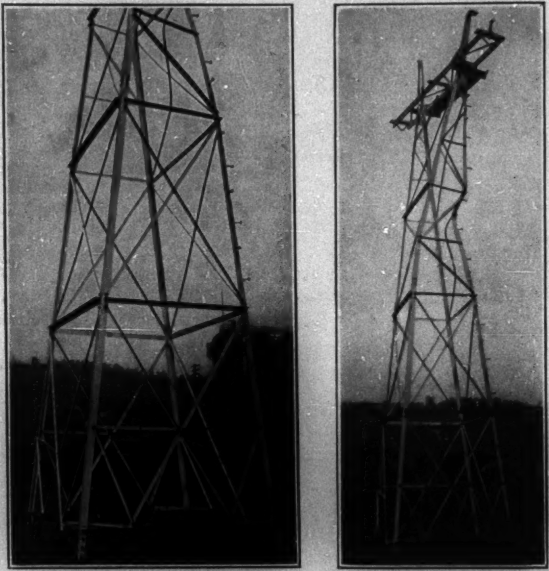
To resist the horizontal force is also a simple matter if the tower is so constructed that all the horizontal shear is taken up in the legs, as would be the case in the tower of Fig. 1, but on account of the necessary separation of wires and other conditions it is usually more economical to use construction illustrated by Figs. 2 and 3. In Fig. 2 all the horizontal force must be taken care of near the surface of the ground, but in Fig. 3 due to the batter in the legs, a part of it is taken by them directly to the base, the remainder must be taken care of near the surface of the ground.

It may be proper to note here that the failure of many towers has been due, at least in part, to the fact that proper provision was not made for this horizontal force.

The most of the failures of which I have reports have occurred on towers with anchors as shown in Fig. 6 with concrete omitted, which is a very common type. With this type there is very little resistance to the horizontal component of the stress in the bottom diagonal. The consequent horizontal movement of the main body of the tower causes buckling in the compression leg. A horizontal strut near the ground level preserves the shape of the tower, but tends to cause buckling in the compression stub and also is generally more expensive than the use of anchors of Figs. 7 and 8. This type may, however, be used if care be taken in the design of the tower to see that there is a small stress in the bottom diagonal.

There are several effective methods used in constructing anchors to resist this horizontal force, such as illustrated in Figs. 5 to 8 inclusive.

Fig. 5 shows an all-concrete anchor to which the tower leg is held by means of anchor bolts.



[LEEPER] [LEEPER]

SHOWING FAILURE OF TOWERS

TOWER FOOTINGS [LEEPER]

Fig. 6 shows a combination of concrete and steel, the leg extending down into the concrete with lugs at the bottom to give bearing on the concrete; the legs being spliced a little above the top.

Fig. 7 shows an all-steel design, using four battered angles extending from a point slightly above the ground level to a base at the bottom. It resists the vertical load by means of a system of angles around the bottom as shown, and the horizontal force by the batter of the upright angles. The objection to this type is that it must have a perfectly flat bottom on which to rest, or unequal stresses will exist in the different legs of the anchor. This design is in use on the Big Creek Line of the Pacific Light and Power Company, and others, and although somewhat expensive on account of its weight and character of shop work, should prove very satisfactory if properly set. There are other anchors of this type but this seems to be the best, everything considered.

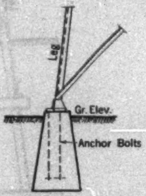


Fig. 5—Showing Concrete Footing with Anchor Bolts for Attaching the Lower Leg

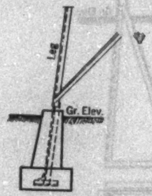


Fig. 6—Showing Concrete Footing with Leg Angle Attached to Stub Angle which Extends into the Concrete

Fig. 8 shows an all-steel anchor which has proved very satisfactory, and as far as I know, the least expensive anchor of efficient design that has yet been constructed. In this anchor as shown, the vertical force and part of the horizontal force is communicated through the single stub angle to a steel grillage, the balance of the horizontal force being taken up about two ft. below the ground level by extending the bottom diagonal of the tower down to the stub angle at that point, where a channel or plate of sufficient area is placed to resist most of the load. This style of an anchor has several advantages:

1. The leg splice to the stub can be kept far enough above ground to be out of the zone of serious corrosion.

2. It can be made practically permanent by splicing the stub about three ft. below the ground, making it possible to renew the part of the anchor at the ground level with small expense.

3. Ease of setting, back filling and tamping properly.

4. Small amount of steel necessary and inexpensive shopwork.

The accompanying photographs illustrate the ability of this style of anchor to resist all the loads which are applied to it. In each test that has been made on towers set on these anchors the break has been due to other causes than the movement of anchors.

In this connection I wish to state that we have very few definite data, secured from actual tests, which show the effect of the applied loads on the anchors and towers when taken together. I think this is due to the fact that engineers when specifying their tests do not state clearly how the tests are to be made and as a result the towers to be tested have been set on a rigid foundation, which does not show how the tower would act on its foundation in the field, unless they are to be rigid.

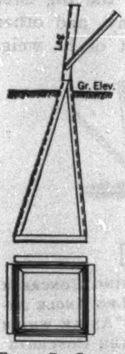


Fig. 7—Showing All-Steel Footing for Earth Setting

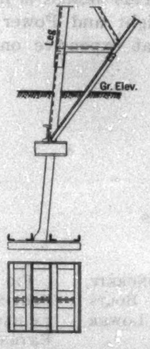


Fig. 8—All-Steel Footing for Earth Setting

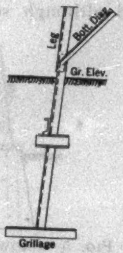


Fig. 9—All-Steel Footing with Horizontal Force in Bottom Diagonal not Properly Provided for

This fact was shown about two years ago when some tests were being made under the direction of Mr. Mershon on some towers for the Inawashiro Hydro Electric Power Company. These towers and their anchors were made as shown in Fig. 9. The bottom diagonal of thet ower is attached to the leg of the tower above ground. We found that the tower always failed in the bottom panel when set on its own anchors, but might fail anywhere if tested on a rigid foundation.

In general, anchors should be stable, permanent and economical.

Concrete anchors are stable and permanent, but in most cases will be found too expensive and sometimes their cost is prohibitive.

Steel anchors, if properly designed and set, can be made practically as permanent as concrete and are much less expensive.

It should be remembered that there are parts of a tower that may fail without causing complete collapse of the tower, but the anchors are not among these parts.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

III—THE ALABAMA POWER CO.

BY W. E. MITCHELL

ABSTRACT OF PAPER

The development of the type of all-steel tower footing used by the Alabama Power Company for their 110,000-volt double-circuit steel tower transmission lines is outlined, with a summary of the conditions influencing the designs finally arrived at.

IT HAS BEEN the writer's opinion for some years that concrete foundations for steel transmission line towers in most sections of the country were not warranted. Due to the inaccessibility of most lines and the impossibility of finding proper concrete materials near them, the cost of concrete foundations, including excavation, frequently runs above $100 per tower and seldom goes below $50.

At the start of the development of the Alabama Power Company a careful investigation was made of the general territory through which the lines were to run with particular reference to railroad and wagon road facilities and concrete materials. It was found the roads were bad and hauls of from four to ten miles from the nearest railway stations were frequent. It was also found that while all lines ran through country with a good clay or disintegrated rock soil, there was practically no sand, gravel or hard rock available for concrete. Studies were therefore made of all-steel foundations and the first 1000 towers were supplied with footings as shown in Fig. 1.

The towers were designed for two circuits of No. 00 seven-strand medium hard drawn copper and two ⅜-in. Siemen's Martin ground wires. The average span was figured as 750 ft. and maximum span 1000 ft. Minimum ground clearance for conductors 25 ft. The loadings used were eight pounds per square foot of projected area of conductors and sixteen pounds per square foot on flat surfaces. Ice loading was taken as ½ in., as in the section the development is in, sleet is practically unknown. Temperature variation 100 deg. fahr.

The test loads on the towers were:

No. 1 A horizontal pull in direction of line of 3000 lb. at any insulator or ground wire support.

No. 2. A vertical load of 1200 lb. at end of any one or all cross arms.

No. 3. A horizontal pull, transverse with line, of 5000 lb. applied at middle conductor cross arm on center line of tower and at the same time a load of 7000 lb. parallel with line, applied at the top conductor cross arm on center line of tower.

Specifications for tower material were:

Material: A. R. E. Association O. H. structural steel.
Unit stresses: Tension, 25,000 lb. per sq. in.

$$\text{Compression, } \frac{25000}{l + \dfrac{l^2}{18000\, r^2}}$$

Bolts: Shear, 20,000 lb. per sq. in.
Bearing, 40,000 lb. per sq. in.
All material galvanized, except bolts to be sherardized.
Connection bolts, ½ in. diameter. Ladder bolts ⅝ in. diameter.
Anchorage connection bolts, ⅝ in. diameter.

With the above data for designing the towers proper, the design of the footings was arrived at as follows:

Experiments with buried disks and other flat plates show that in pulling them up the soil is removed in the form of a cone and that the angle of the sides of the cone very closely approximates the adherence angle of the soil. In determining upon the size of the footing and the depth to which it should be put, it was assumed that the maximum force withstanding tension in the tower stub was the weight of an inverted truncated cone of earth which had the area of the tower footing as the smaller base and sloped outwardly at an angle of 30 deg. from the vertical. The weight of the soil was assumed as 100 pounds per cubic foot. In this calçulation no account was taken of the unknown but ever present friction between the soil in the cone and the surrounding soil.

To withstand a thrust on the footing, a fair bearing pressure per square foot was assumed. By these calculations it was found that a base about 6.25 square feet in area and buried 7.5 feet in the earth would give a factor of safety of two. The lightest grillage for this given strength therefore was 2.5 feet square.

In the field work it was found that it was necessary to dig a hole at least 2.5 feet by 3.5 or 4 feet in order to allow the men sufficient room in which to work. It was evident therefore that an anchor of rectangular shape would require less excavation and for that reason the later towers were ordered with anchors 2 feet by 3.5 feet in area. The grillage weighed more but the saving in field work more than offset the greater cost of metal.

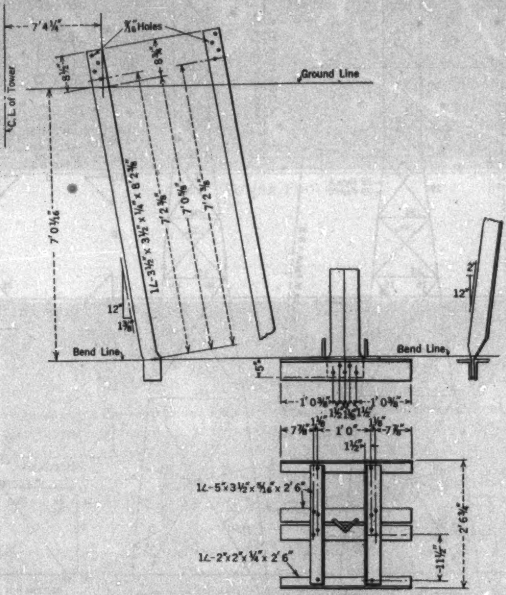

7′4¼″
⁹⁄₁₆″ Holes
C.L. of Tower
8½″
8¾″
Ground Line
7′0¹⁄₁₆″
1∠-3½″ x 3½″ x ¼″ x 8′2⅜″
7′2⅜″
7′0⅝″
7′2⅜″
12″
1⅜″
Bend Line
5″
1′0⅜″
1′0⅜″
1½ 1⅛ 1½
7⅞″
1⅛″
1′0″
1⅛″
7⅞″
1½″
1∠-5″x3½″x⁵⁄₁₆″x 2′6″
1∠-2″x2″x¼″x 2′6″
11½″
2′6¾″
2″
12″
Bend Line

FIG. 1—FOOTING FOR TYPE "A" TOWERS

In tests and in the field where the erected towers were subjected to heavy overturning strains, it had been noticed that the legs tended to move toward each other at the ground line, showing that the earth, though well tamped around the stub, would yield to the horizontal stress in the lowest diagonal. At this point the tower leg must resist a force at right angles to its loading, and this force acts upon a very long lever beam. To care for this force, it was decided to make the point of junction of the lowest diagonal and the tower leg, about 2.5 feet below the ground

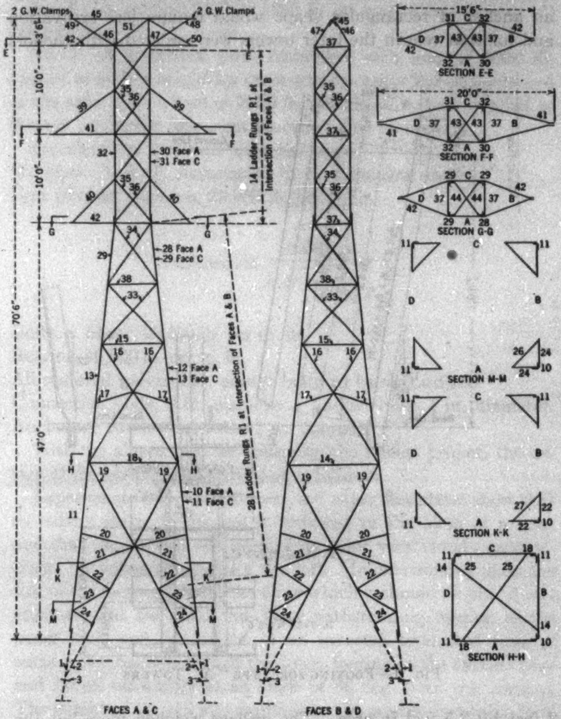

2 G.W. Clamps
2 G.W. Clamps
3'6"
10'0"
10'0"
70'6"
47'0"
14 Ladder Rungs R1 at Intersection of Faces A & B
28 Ladder Rungs R1 at Intersection of Faces A & B
30 Face A
31 Face C
28 Face A
29 Face C
12 Face A
13 Face C
10 Face A
11 Face C
E
F
G
H
K
M
FACES A & C
FACES B & D
15'6"
SECTION E-E
20'0"
SECTION F-F
SECTION G-G
SECTION M-M
SECTION K-K
SECTION H-H
A
B
C
D

FIG. 2—ERECTION DIAGRAM

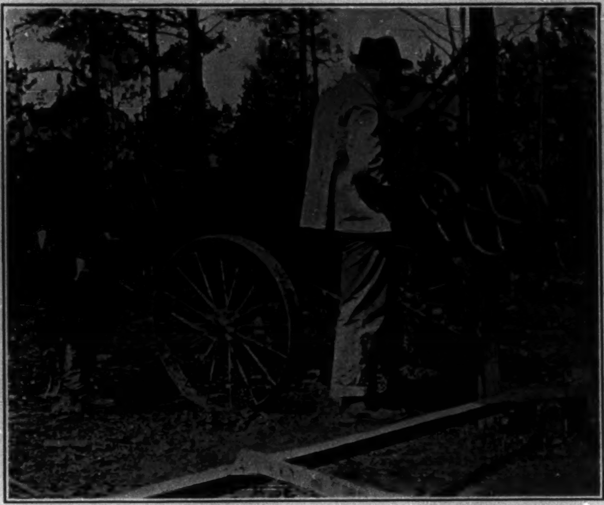
line and there put in some horizontal resisting surfaces. These latter were made of two pieces of 6-in. channel 18 in. long bolted to the leg at right angles to each other. A tower with these modifications of the footings and lower diagonals was tested to destruction. The bolts in the upper part of the tower, as shown

"A" TOWER FOOTINGS [MITCHELL]

SETTING FOOTINGS [MITCHELL]

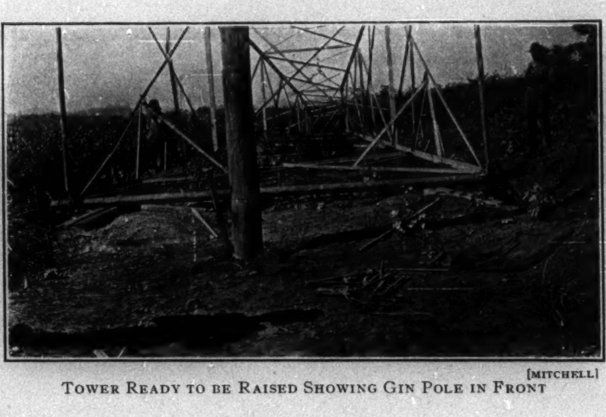
GASOLINE AIR COMPRESSOR AND JACK HAMMER DRILL [MITCHELL]

ROCK ANCHOR [MITCHELL]



[MITCHELL]

GASOLINE TAMPER



[MITCHELL]

TOWER READY TO BE RAISED SHOWING GIN POLE IN FRONT

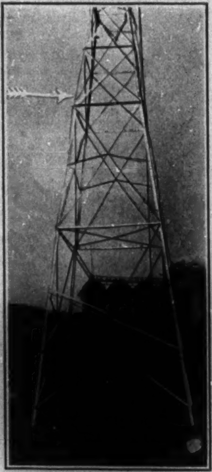
[MITCHELL]

ERECTING TOWERS

[MITCHELL]

LOWERING TOWER ON TO STUBS

PLATE LX.
A. I. E. E.
VOL. XXXIV, 1915



[MITCHELL]

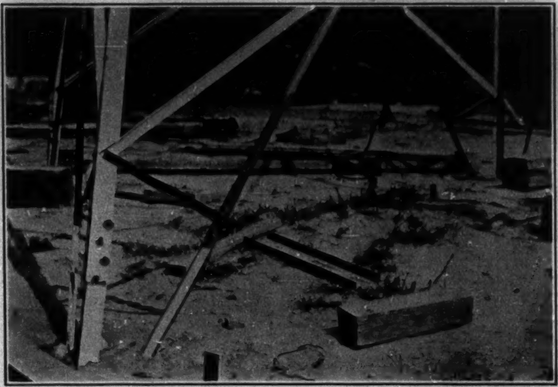
"A" TOWER AFTER APPLICATION OF TEST LOAD OF 12,000 LB.

Eight ¾-in. bolts sheared in leg as shown by arrow.

[MITCHELL]

LEG OF TOWER AFTER APPLICATION OF TEST LOAD OF 12,000 LB.

Showing crack in earth and condition of soil in which tower was set.



[MITCHELL]

VIEW OF "A 1" TOWER AT GROUND LINE

by the arrow in one of the illustrations, sheared; the legs of the tower as evidenced by the ground at the base had not moved. These changes produced a tower which we believe has no superior for the same weight.

In traversing such rough country, it was frequently necessary to locate the towers, or one or more legs at least, on a bed of rock. In some cases, the rock was decayed enough to make the use of a grillage footing advisable; in many cases however the foundation was of such stable character that it was practically necessary to use some type of rock anchor. This feature was studied and as a result, the anchor shown in Fig. 3 was developed. It is an angle the same size as the leg angle of the tower which at the lower end has been rounded and scarfed. A hole 2.25 inches in diameter was drilled and the anchor grouted into place. This formed a footing which was materially cheaper and easier to install than the use of a special tower footing with the two or more anchor bolts.

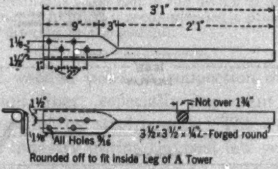


FIG. 3—ROCK FOOTING FOR "A" TOWERS

In excavating, hand drills, coal augers, and a portable gasoline-driven air compressor with a jack hammer drill were used. Forty per cent dynamite was used and practically all holes were shot. The coal augers did not prove satisfactory. The compressor outfit however effected a saving of about 25 per cent over hand drilling. The drawback to it was that it could not be used in very rough country due to the impossibility of getting it near the tower location.

Towers were located by the field engineer from the spotting made in the office on a profile of the line. Reference hubs were set and depth of excavation for each footing marked. All four footings were set at one time using a template, and were leveled up with a carpenter's level and level board, or with an engineer's Y level. The backfill was carefully tamped by hand. Experiments with a regular gasoline-driven ditch tamper showed very good results where it could be used, but the roughness of the country prevented its use to any large extent.

Examination of footings after one year show only very slight settlement and no movement of tower base whatever. Towers were assembled complete on the ground, the insulators hung on the crossarms, and then raised with a gin pole. The average assembling crew assembled from twelve to sixteen towers per day and the erecting gang raised about the same number. The best record was twenty towers raised in one ten-hour day.

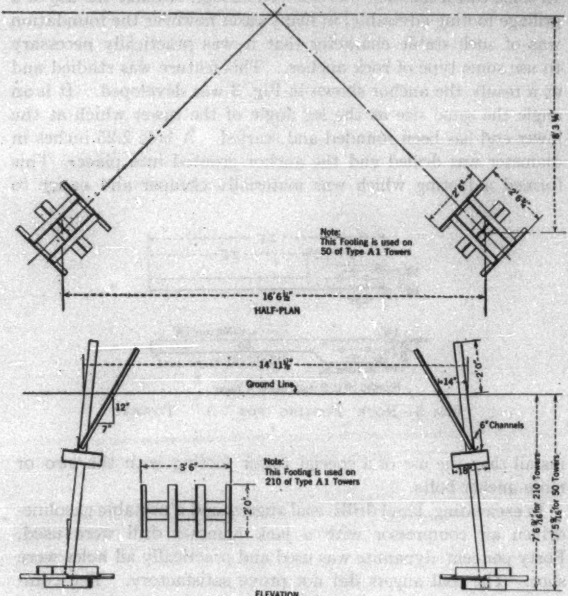

2'6"
2'6½"
8'3¼"
Note:
This Footing is used on
50 of Type A1 Towers
16'6½"
HALF-PLAN
14'11½"
2'0"
Ground Line
14"
12"
7"
6" Channels
3'6"
Note:
This Footing is used on
210 of Type A1 Towers
2'0"
18"
7'6 9/16" for 210 Towers
7'5 9/16" for 50 Towers
ELEVATION

FIG. 4—FOOTING USED ON 50 TYPE "A1" TOWERS

Excavation, setting footings and back fill, with all steel foundations, cost on an average of $28.00 per tower; assembling 4800-pound towers cost $10.00 and erection $5.00.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

IV—A FEW ESSENTIALS IN TOWER LINE CONSTRUCTION

BY P. M. DOWNING

ABSTRACT OF PAPER

In this paper the author briefly emphasizes the fact that the weakest link of any transmission system is the line, and that this part of the plant has never been given the consideration it deserves.

Towers are strongly advocated for important trunk lines, and certain conditions to be met in the design of same are given. The use of concrete footings is recommended in preference to those of metal set directly in the ground.

THE USE of wooden poles in connection with high voltage transmission lines, especially important trunk lines, is fast being superseded by steel towers. The wonderful growth of the electrical industry during the past few years has resulted in the construction of larger generating stations, and the transmission lines carrying these heavier loads have become of correspondingly greater importance.

During all of this time, except for a noticeable increase in the sizes of the units used, there has not been any radical change in the equipment of hydroelectric generating stations. The same general types of turbines and impulse wheels as were used fifteen or twenty years ago, during the infancy of the industry, are still being used. Slight modifications in the design of the generators, the use of the better material now available, and higher speeds have resulted in larger units and increased efficiencies. Transformers have kept pace with the generators and waterwheels, both as regards size and efficiency, but have never been in any respect the limiting feature in high-voltage transmission work.

The line is and has always been the weakest link of the entire system, and it is only during the last few years that this part of the work has received the attention it deserves. Wooden pole lines with pin type insulators were for many years used almost exclusively, regardless of the voltage, or the importance of the line; in fact, it was not until 1903 that the first commercial tower line in America was constructed by the Guanajuato Power Co., in Mexico. The first line using towers with suspension insulators was the 140-mile 100,000-volt line of the Stanislaus Power Company in California (now the Sierra and San Francisco Power Co.).

The tower designs first constructed called for each structure to be self-supporting under strains due to the breakage of all conductors on one side of the tower together with maximum ice and wind strains. This resulted in a heavy, durable structure of high first cost, and imposed a very much more severe condition than could be met by pole lines.

Little attention had ever been given to the determination of the strength of wood poles, either by calculation or actual test, and there is no doubt but that such strength requirements in line towers were unreasonable. Subsequent experience has shown that the average tower is too complicated a structure to accurately calculate the stresses in the different members, and it is now generally conceded that the best and only safe way to get reliable information as to the stability of a tower, is to subject it to actual test.

A very safe condition under which to test towers to be used in a country not subject to severe snow and sleet conditions, is to consider a wind pressure of 14¼ lb. per sq. ft. on flat surfaces, combined with a temperature range of 125 deg. fahr., or a pressure of 21 lb. per sq. ft. on flat surfaces under ordinary temperatures; also two broken wires in any span of a circuit carrying six wires. These breakages to be in such positions on the tower as will give maximum strain. The height of the tower will depend on the spacing and the required clearance of the conductor above the ground. Considerable difference of opinion exists as to the most economical length of span that can be used. These range from 400 to 1200 ft., depending to a considerable extent on the character of the country, the climatic conditions and the voltage of the line.

Where the line is subject to heavy snow and sleet conditions, the spans must be short, and very often under such conditions it is inadvisable to place the three conductors in a vertical plane. A very much better and safer construction can be had by using single circuit towers with the conductors in a horizontal plane. Under these conditions any unequal distribution of the snow load on the different conductors will not cause them to come in contact with each other. On 100,000-volt lines carrying two circuits of three wires each, located in vertical planes on the two sides of the tower, a spacing of 800 to 1000 ft. will generally be found to give maximum economy.

Tower foundations depend largely on the character of the soil in which they are located. In heavy ground a metal footing having sufficient resistance against up-lift may be used, but they are not to be recommended. The permissible strains borne by well tamped dry earth do not always obtain under water soaked flood conditions. Where metal footings without concrete have been used, too often they have been found inadequate and resulted in the ultimate failure of the tower. Under no circumstances, except on very short towers, should single post footings be used. Two or three posts give a much more rigid and substantial construction, but materially increase the first cost of the structure; in fact, for the same factor of safety, it is very doubtful whether under any normal conditions the difference in first cost between the metal and concrete footings will be great enough to justify a decision in favor of the metal.

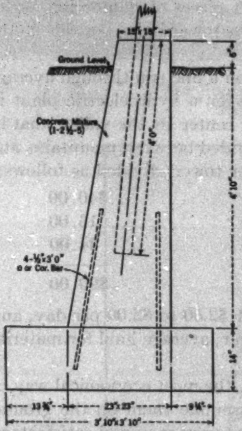


Fig. 1—Concrete Footing for 75-Ft. Double Circuit Line Tower

On a number of different lines originally constructed with all metal footings, tower failures have occurred, and it has since been found necessary to reinforce them with concrete.

On the basis of an 800-ft. spacing between towers, and an allowable stress of 15,500 lb. per sq. in. for copper conductors, the sag at 60 deg. fahr. would be approximately, 20 ft. On a double-circuit tower line, having conductors strung to this tension and spaced 10 ft. apart, with a required clearance of 30 ft. above the ground, a 75 to 80 ft. tower would have to be used. The footings of a tower of this height under the assumed load conditions should contain not less than 1½ cu. yards of concrete per leg, and be of a form similar to that shown in Fig. 1. On the basis of concrete weighing 140 lb. per cu. ft., earth 110 lb. per cu. ft., and assuming the angle of cleavage of the earth as 30 deg. from the vertical, a footing of this kind would have a factor of safety of approximately two.

In pouring the concrete in a footing of this kind the bottom pan-cake is placed without a form, and allowed to set just long enough to support a metal form for the upper portion.

To insure against weakness due to possible poor bonding along the plane of contact between the upper and lower portions of concrete, it is advisable to use short pieces of reinforcing, or let the metal footing extend well down toward the bottom of the foundation.

The cost of footings of this kind on a line run through average country such as will be found between a hydroelectric plant in the mountains, and a distributing center in the valley, that is, where the route is about equally divided between mountains and valley, is, approximately, $90.00 per tower, divided as follows:

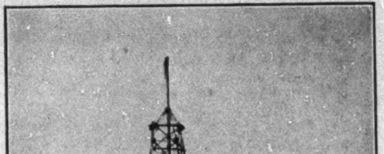
Labor	$40.00
Material	16.00
Hauling material	34.00
	$90.00

These prices are based on labor at $2.50 to $3.00 per day, and concrete mixed by hand at each tower; average haul for material six to eight miles.

In a country that is not too steep, the most economical way of erecting towers of this size is to assemble them on the ground and end them up into position. One very easy and satisfactory way of doing this is to set a 30 or 35-ft. gin pole just outside of the footings holding it in position by three guys fastened to iron stakes driven into the ground for anchors. Over an open sheave on the top of this gin pole is carried a 0.5-in. flexible steel cable one end of which is connected to the tower at the lower cross-arm, the other to a set of triple blocks made fast to another anchorage 300 or 400 feet from the base of the tower. Where the ground around the footings is not well packed, it is advisable to use hold back anchors on the ground legs, as otherwise the heavy pull against the footings when the tower starts to raise is liable to damage them. A back guy should also be provided to prevent the tower dropping into place as it comes up to a vertical position. Ordinarily side guys are unnecessary, but during windy weather it is well to have them held loosely as the tower rises.

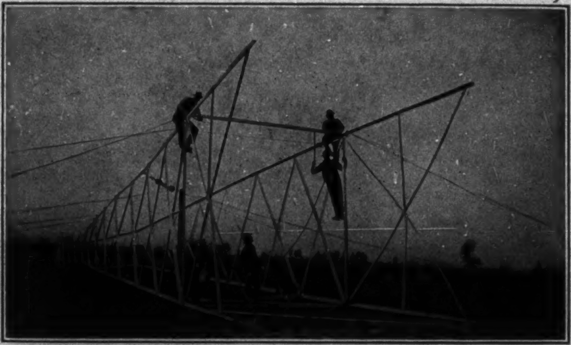
[DOWNING]

FIG. 2—PLACING TOWER FOOTINGS ON A STEEP SIDE HILL BY MEANS OF METAL TEMPLATE



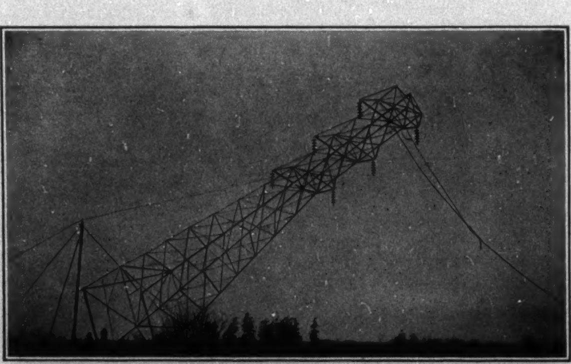
[DOWNING]

FIG. 3—A STEEL TOWER BEING ERECTED AT LINE CROSSING OVER A NAVIGABLE STREAM. Showing a gin pole in the middle of the tower and supported from the four corners of the tower at both bottom and near the top by means of blocks and tackle



[DOWNING]

FIG. 4—A SEVENTY-EIGHT FOOT DOUBLE CIRCUIT STANDARD LINE TOWER BEING ASSEMBLED ON THE GROUND



[DOWNING]

FIG. 5—A TOWER BEING RAISED INTO POSITION BY MEANS OF A GIN POLE

The best motive power for this work is a 3-ton motor truck which can be used not only for raising the towers, but also for transporting tools and equipment between towers. A crew of nine men with a truck will raise and fasten to the footings an average of 9 towers per work day of 8 to 9 hours. The insulators are attached to the tower while it is on the ground and raised with it.

While there are few, if any, tower lines that have been in service long enough to determine the relative merits as between galvanizing and painting of steel structures of this kind, there is every reason to think that hot dip galvanizing when properly done will prove the more satisfactory in the end. The first cost of painted towers is less than galvanized, but at the very best, the painting will last only a few years. As an offset to the lower first cost of painting, there would be the increased maintenance cost. Moreover the tops of the tower could not be painted with voltage on the line. To do this part of the work, service would have to be interrupted. This objection alone would in many instances be a most serious one, and doubtless, would oftentimes be the determining factor in deciding in favor of the galvanized structures.

There is nothing, thus far, to indicate that there is any appreciable deterioration of the galvanizing when set either in the concrete or directly in the ground. Galvanized tower bolts are not entirely satisfactory. It has been found that almost invariably the bottom of the threads will be so filled up with the galvanizing that the nuts cannot be run on. Sherardizing overcomes this trouble, but is open to the objection that this process is inferior to hot dip galvanizing, and it is often only a matter of a short time when the sherardizing will disappear and the bolts rust. After the tower is erected it should be gone over carefully, all bolts tightened and the threads upset, so that the nuts cannot work loose.

Unless this is done the vibration of the tower due to the wind will, within a few months or a year, cause the nuts to loosen and back off a turn or two, thus materially reducing the rigidity of the tower. This same thing will happen on the clamp bolts holding the conductor, unless lock washers, or some other means, are provided to prevent it.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION

V—TORONTO POWER COMPANY

BY F. C. CONNERY

ABSTRACT OF PAPER

There is a broad field open for designing and construction engineers in the design and construction of transmission towers and foundations. The purpose of the paper is to present a brief explanation of the types of towers, tower foundations, etc., along with a few details of field practise used in connection with the construction of two lines of towers carrying six 190,000-cir. mil, seven-strand copper conductors between Niagara Falls and Toronto, Ontario.

The question of dispensing with massive concrete foundations for towers is dealt with, and a number of alternatives are presented for consideration.

THE following notes relate to the old and new 60,000-volt lines of the Toronto Power Company, between Niagara Falls and Toronto.

There are several types of towers and foundations used on these lines which are outlined in Figs. 1 to 5 inclusive. Figs. 6, 7, 8, 9 and 14, are reproduced from photographs showing various features of interest of certain of these towers.

Towers enumerated above, with the exception of that of Fig. 3, are designed to carry two circuits of 190,000-cir. mil seven-strand copper cable, for 60,000-volt transmission; pin-type insulators are used. The tower of Fig. 3 is designed to carry four circuits of the same size conductor.

The writer will endeavor to give, from a practical view-point, a brief explanation of a few of the foundations used with the above mentioned towers.

Fig. 10 shows foundations used in connection with tower shown in Fig. 1. About 100 sets of these footings have been dug up after being in use seven years, and in no instance has the galvanizing deteriorated, and the 3 by 6 by 24-in. impregnated wooden blocks, with a few exceptions, were in a fair state of preservation. These foundations were located in various kinds of soil.

In connection with the tower shown in Fig. 2, we did not use impregnated blocks, nor were any precautions taken, other than the hot-galvanizing, to prevent corrosion of the steel. Six of these towers were erected in low marshy black-muck, no resistance being encountered with borings at 40 ft.

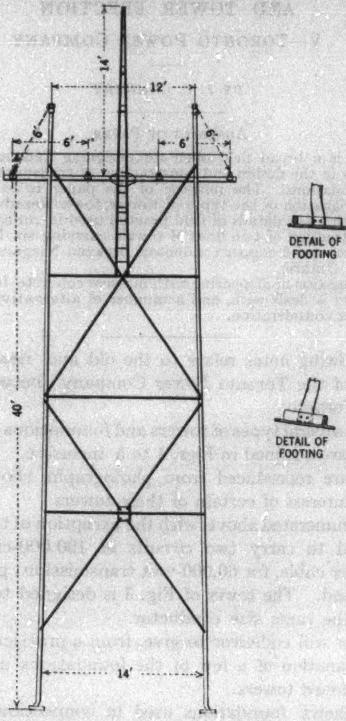
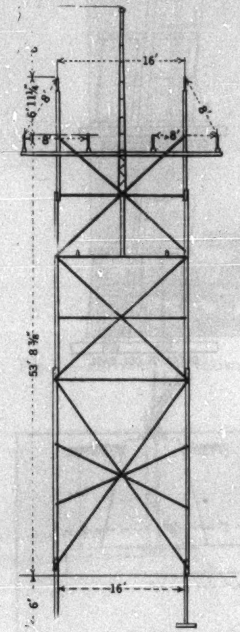
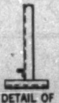


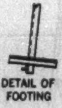
FIG. 1—STANDARD TOWER WITH GROUND SPIRE

A two-inch plank sheathing was driven around each tower-leg location, the muck dug out and a floating foundation built six feet below the ground surface; this consisted of impregnated two-inch planking, the footings being set in concrete, approximately one yard of cement being placed around and under each stub, the excavations being 30 in. by 30 in. by 6 ft. These towers have been erected for one year and have neither settled nor gotten out of alignment.

I may say that great care was taken in connection with the locating of towers, so as to avoid, where possible, soft marshy soil and also to equalize the grade. Tower footings in gravel, or a mixture of sand and loam packed tightly, offer a great resistance against upward pull.







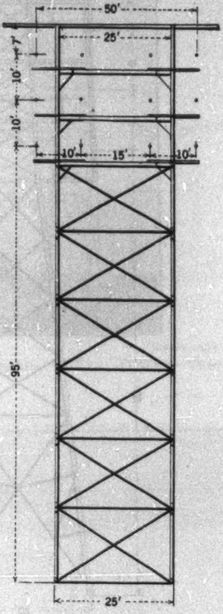


FIG. 2—STANDARD 53-FT TOWER.

FIG. 3—FOUR-CIRCUIT LAKE TOWER

A number of towers of the type marked Fig. 2, were erected in rock. This rock was thinly stratified and was easily excavated to a depth of three feet. The stubs were cut down to 3 ft. 6 in., and were concreted in with a one-to-four mixture. This construction has proved satisfactory.

In Figs. 6 to 9 is shown a type of narrow-base latticed tower. The foundations for these were built in two ways.

(a) A foundation 6 ft. by 6 ft. by 6 ft. with twelve 1¼-in. anchor bolts 5 ft. 6 in. long. This was a one-three-five concrete mixture.

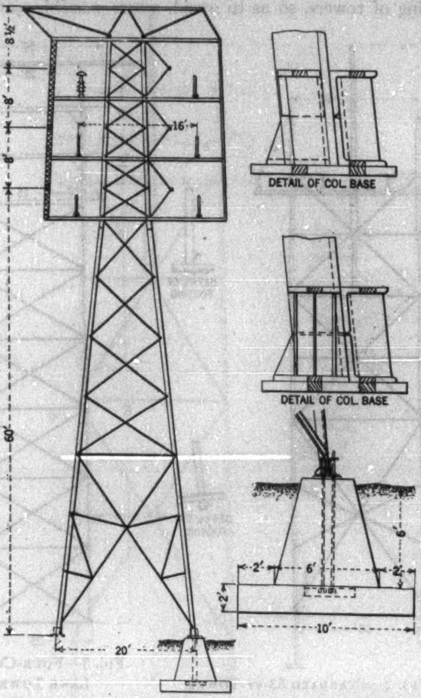
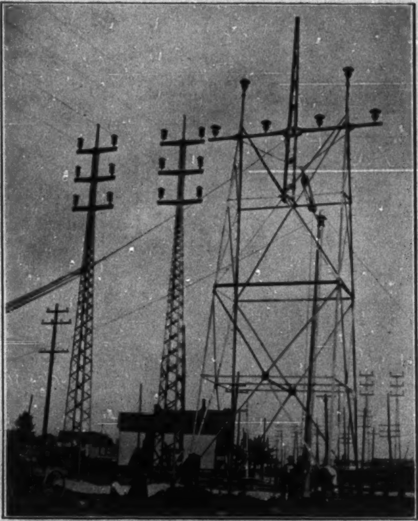


FIG. 4—ANGLE TOWER FOR ANGLES TO 60 DEGREES

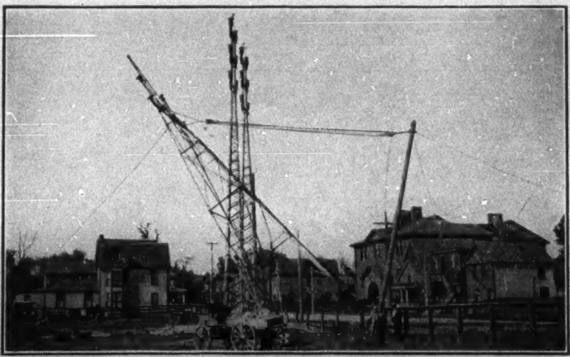
(b) Foundations 6 ft. by 6 ft. and varying in depths were built in the following manner:

Excavation was taken out, copper grounding-ribbon placed, and 12 inches of one-three-five concrete placed and tamped.



[CONNERY]

FIG. 6—METHOD OF LOWERING STANDARD 40-FT. TOWER—FIRST POSITION



[CONNERY]

FIG. 7—METHOD OF LOWERING STANDARD 40-FT. TOWER—SECOND POSITION

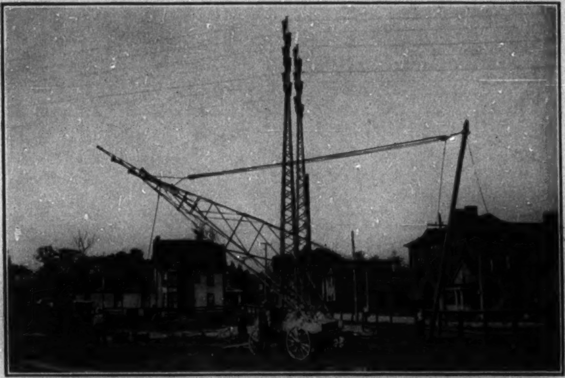


FIG. 8—METHOD OF LOWERING STANDARD 40-FT. TOWER—THIRD POSITION

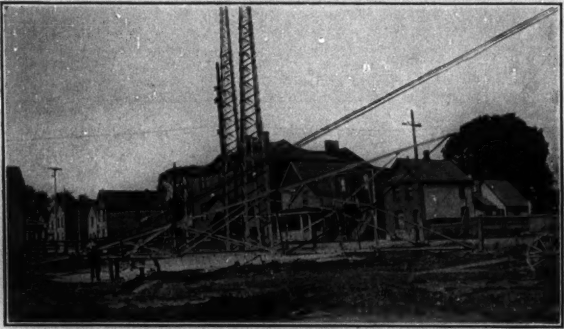
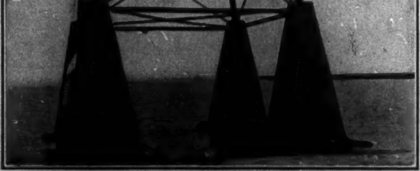


FIG. 9—METHOD OF LOWERING STANDARD 40-FT. TOWER—FOURTH POSITION



[CONNERY]

FIG. 14—LAKE TOWER FOUNDATIONS, BURLINGTON BEACH

No anchor bolts were used, but the tower was erected on this 12-in. base, and then the excavation filled with one-three-five concrete, this method being used on account of the variation in the dimensions of the bases of these towers. Minimum depth six feet.

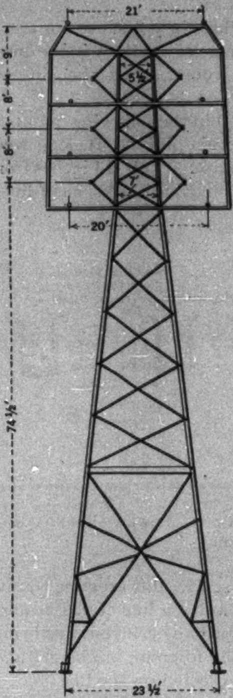


FIG. 5—HEAVY 75-FOOT STRAIN TOWER

Construction of Footing. (Fig. 3) Eleven of the above footings were constructed in the waters of Lake Ontario at Burlington Beach, Ontario, the mean depth of water being about three ft.

A double coffer-dam was built of 2 by 8-in. tongued and grooved spruce, driven to a depth of 10 feet below the lake bottom by a small steam hammer. The water was pumped out, and sand and gravel excavated to a depth of six feet below the lake bottom, where very coarse gravel was encountered.

The foundations were then constructed as shown, the spruce sheeting being left in to protect against scouring. After the foundations were complete, a talus of 10-inch rock, each piece weighing from 500 to 1500 lb., was built around the two outer footings of each foundation for extra protection, the location of these towers being on a shore where storms from the East are very prevalent.

Method of Setting Stubs. Fig. 15 shows the template used with success in the setting of stubs. This template was carried by the setting-gang, lined up on the center line stakes and leveled by the gang foreman by means of a carpenter's level, and then blocked up and checked.

The stubs were bolted to the template and the filling in of holes proceeded with. One man back-filled while two men tamped. Special attention on the part of the foreman should be given to the tamping, as workmen are apt to do this in a careless manner.

Where water was available it was used to settle the back-filling.

The towers were assembled at the locations where they were to be erected, and were erected with a shear-leg outfit. From eight to twelve towers of the type marked Fig. 2 were erected in one day by eight men and one team.

The writer has used portable derricks, gin-poles, etc. for erecting towers, and can say that the shear-leg method is the most efficient, except where cramped for room, when the gin-pole should be used.

The shear-legs used were constructed in the following manner: two pieces of 6-in. by 8-in. clear Georgia-pine, 34 ft. long were bolted together with a 1-in. by 14-in. through bolt, 14 inches from the top. This along with a set of 12-in. triple blocks, hand-lines, anchor-pins, etc., makes a cheap and serviceable erecting outfit. The above outfit was used in the erection of a line of 928 towers averaging 2¼ tons each, and only one mishap occurred, this being caused by negligence on the part of the foreman in charge, and was in connection with the first tower erected on the line.

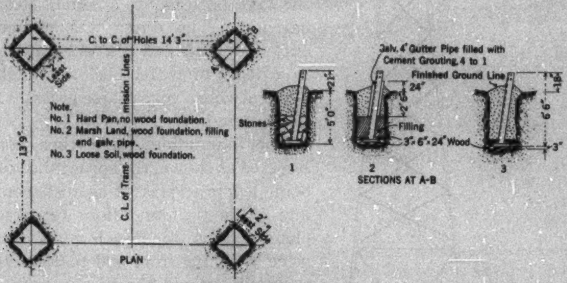

C. to C. of Holes 14' 3"
A
B
2' Least Side
C. L. of Transmission Lines
13' 9"
Note.
No. 1 Hard Pan, no wood foundation.
No. 2 Marsh Land, wood foundation, filling and galv. pipe.
No. 3 Loose Soil, wood foundation.
PLAN
Galv. 4" Gutter Pipe filled with Cement Grouting, 4 to 1
Finished Ground Line
Stones
21"
5' 0"
24"
2' 6"
Filling
3"×6"×24" Wood
18"
6' 6"
3"
1
2
3
SECTIONS AT A-B

Fig. 10—Diagrams of Standard 40-Foot Tower—Foundations in Different Soils

Notes on Guy Anchors

Patent anchors for guying should not be used other than for light construction. In light soil, an old fashioned slug, or deadman, gives the best results. All guys should be periodically inspected and tightened up. When more than one guy is used on a pole, galvanized turnbuckles should be used to obtain best results.

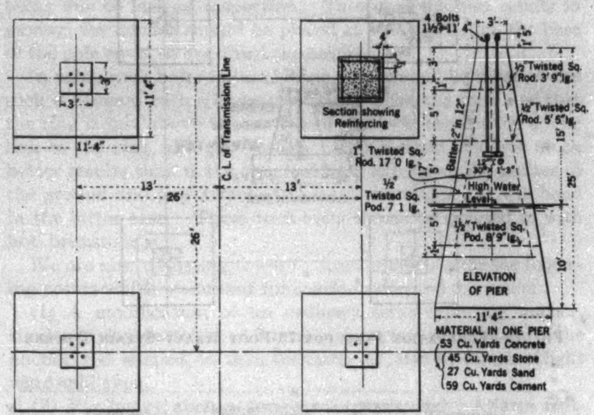

3'
3'
11' 4"
11' 4"
4"
Section showing Reinforcing
C. L. of Transmission Line
13'
13'
26'
26'
4 Bolts 1½"×11' 4"
3'
1' 5"
½" Twisted Sq. Rod. 3' 9" lg.
½" Twisted Sq. Rod. 5' 5" lg.
1" Twisted Sq. Rod. 17' 0" lg.
½" Twisted Sq. Rod. 7' 1" lg.
Batter 2" in 12"
High Water Level
½" Twisted Sq. Rod. 8' 9" lg.
15'
25'
10'
17'
5'
5'
5'
ELEVATION OF PIER
11' 4"
MATERIAL IN ONE PIER
53 Cu. Yards Concrete
45 Cu. Yards Stone
27 Cu. Yards Sand
59 Cu. Yards Cement

Fig. 11—Foundation Plan for Lake Tower

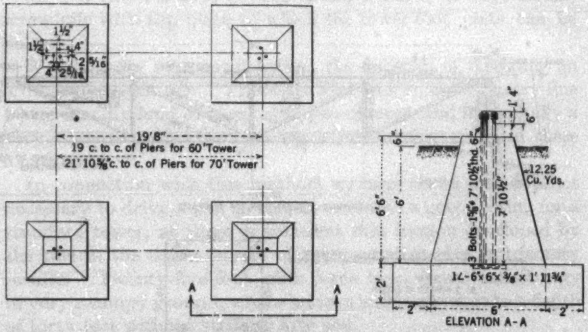

1½"
1½"
4"
2 5/16"
4"
2 5/16"
19' 8"
19 c. to c. of Piers for 60' Tower
21' 10⅝" c. to c. of Piers for 70' Tower
A
A
1' 4"
6"
6"
6' 6"
6'
3 Bolts-1⅝"×7' 10½" thd. 6"
7' 10½"
12.25 Cu. Yds.
1∠-6"×6"×⅜"×1' 11¾"
2'
2'
6'
2'
ELEVATION A-A

Fig. 12—Masonry Plan and Anchor Bolts

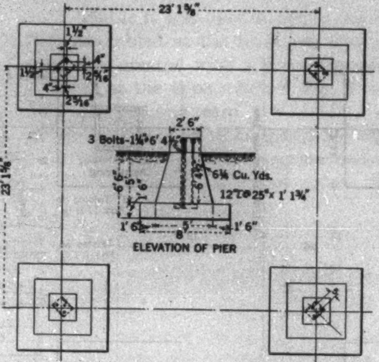

23' 1⅝"
1½"
4"
2 5/16"
2' 6"
3 Bolts-1¼"×6' 4½"
6¼ Cu. Yds.
6' 6"
5'
1' 6"
6' 4"
1' 6"
5'
8'
1' 6"
ELEVATION OF PIER

FIG. 13—FOUNDATION PLAN FOR 75-FOOT HEAVY STRAIN TOWERS

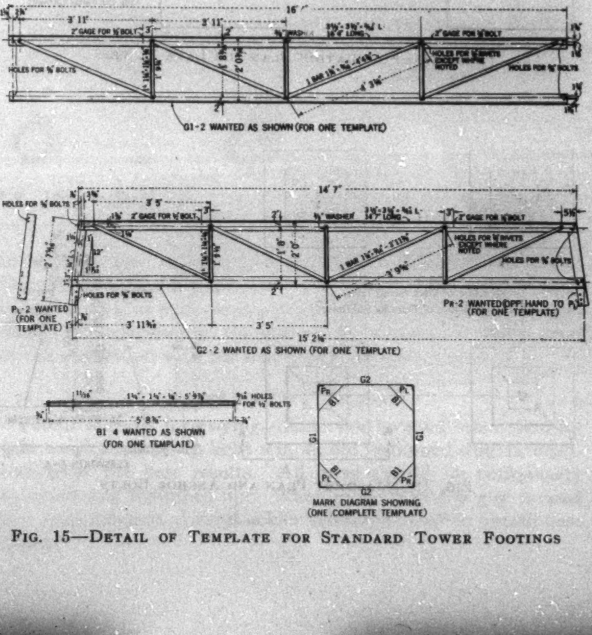

16'
3' 11"
2" GAGE FOR ⅝" BOLT
HOLES FOR ⅝" RIVETS EXCEPT WHERE NOTED
HOLES FOR ⅝" BOLTS
1' 8"
2' 0"
G1-2 WANTED AS SHOWN (FOR ONE TEMPLATE)
14' 7"
3' 5"
½" WASHER
2" GAGE FOR ½" BOLT
PL-2 WANTED (FOR ONE TEMPLATE)
PR-2 WANTED OPP. HAND TO PL (FOR ONE TEMPLATE)
3' 5"
15' 2¼"
G2-2 WANTED AS SHOWN (FOR ONE TEMPLATE)
HOLES FOR ½" BOLTS
B1 4 WANTED AS SHOWN (FOR ONE TEMPLATE)
G2
G1
PR
PL
B1
MARK DIAGRAM SHOWING (ONE COMPLETE TEMPLATE)

FIG. 15—DETAIL OF TEMPLATE FOR STANDARD TOWER FOOTINGS

From observations extending over ten years, I would say that fully 40 per cent of the guys in use are inefficient, this condition being due to lack of inspection. To obtain the best results in guying, the anchor should be placed at a distance from the base of the pole equal to one-third the height.

In using rock-bolts for anchoring, care should be taken, if the rock is covered with a layer of earth, to place the anchor so that the ring is just above the surface of the rock; then fasten a long link to the ring, and guy to this. This method will give much better results than if the ring had been left above the surface of the ground and guy attached to it, as the anchor rod will bend in the latter case. These rock-bolts should be grouted in with hot brimstone.

We are now designing tower footings which include the following points which we submit for consideration and discussion:

(1) A modification of an ordinary screw-type guy anchor, similar to the Matthews or Stombaugh anchor, with the top of the anchor rod shaped to take the tower leg; this for towers of light wind-mill type.

(2) For heavy anchor, long-span towers, etc. A large foot-plate supported on a shallow concrete footing sufficient to give a good bearing, and an anchor similar to those mentioned above, with the exception that the end of the bolt will be threaded to take a nut and locknut.

(3) For extra heavy, or four-circuit towers. A large section screw-pile with top plate to which the tower foot plate can be bolted.

We also offer for consideration, the question of threading an ordinary wooden pile. There are locations on almost every line where marshy land or muskeg is encountered, and it is usually a very expensive operation to use a pile-driving outfit in these locations.

In connection with this method, we have found that it is not necessary to drive a pile to refusal to obtain a good footing for a standard tower, as there is sufficient skin friction developed by the pile in the upper layers of the ground to give satisfactory results. Twenty-five-foot piles have been found satisfactory in very swampy ground, where borings had been taken to a depth of forty feet without striking firm soil.

From other extensive extensions over ten years, I would say that fully 40 per cent of the guys in use are in [illegible] condition, this being due to lack of inspection. To obtain the best results in guying, the anchor should be placed at a distance from the foot of the pole equal to one-third the height.

In using rock-bolts for anchors, care should be taken, if the rock is covered with a layer of earth, to place the anchor so that the ring is just above the surface of the rock, then fasten a long link to the ring and guy to this. This method will give much better results than if the ring was just left above the surface of the ground and guy attached to it, as the anchor rod will bend in the latter case. These rock bolts should be grouted in with hot brimstone.

We are now designing tower footings which include the following points which we submit for consideration and discussion:

(1) A modification of an ordinary screw type guy anchor, similar to the Matthews or [illegible] anchor, with the top of the anchor rod shaped to take the tower leg, this for towers of light wind-mill type.

(2) For heavy angle, long-span towers, etc. A large plate footing with a shallow concrete footing sufficient to give a good bearing, and an anchor similar to those mentioned above, with the exception that the end of the bolt will be threaded to take a nut and locknut.

(3) For extra heavy, or four circuit towers. A large section screw pile with top plate to which the tower foot plate can be bolted.

We also refer for consideration the question of installing an ordinary wooden pile. There are locations on almost every line where swampy land or marsh, is encountered, and it is usually a very expensive operation to use a pile-driving outfit in these locations.

In connection with this method, we have found that it is not necessary to drive a pile to refusal to obtain a good footing for a standard tower, as there is sufficient skin friction developed by the pile in the upper layers of the ground to give satisfactory results. Twenty-five-foot piles have been found satisfactory in very swampy ground, where borings had been taken to a depth of forty feet without striking firm soil.

Presented at the meeting of the Baltimore Section, A. I. E. E., February 26th, 1915, and discussed at the 32d Annual Convention, A.I.E.E., Deer Park, Md., June 29, 1915.

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FOUR YEARS' OPERATING EXPERIENCE ON A HIGH-TENSION TRANSMISSION LINE

BY A. BANG

Abstract of Paper

The Pennsylvania Water and Power Company, since it started operation of its hydroelectric plant at Holtwood, Pennsylvania, has kept a careful record of all operating events. In the following paper this record is given for the four years 1911-1914, as far as the *high-tension transmission line*, Holtwood to Baltimore, is concerned. The record deals essentially with certain observations made on lightning flash-overs, deterioration of insulators, sleet on cables, and the various means adopted to prevent disturbances to operation from these causes.

THE TRANSMISSION line for which the operating record is given herein is the line which transmits energy at 70,000 volts from the Pennsylvania Water and Power Company's hydroelectric plant on the Susquehanna River at Holtwood, to the same company's terminal station at Baltimore, Md., where the current is stepped down for distribution purposes. Practically all the load consists of synchronous machinery, such as synchronous converters, frequency changers, etc.

This line is about 40 miles long and runs mainly in the direction north-south, through a hilly country, on a right-of-way 100 ft. wide. It consists now of two rows of steel towers, each capable of carrying two independent three-wire circuits. The first of these tower lines (No. 12) was built in 1910, with both circuits installed; the second (No. 56) in the summer of 1914. On this latter at present only one circuit is installed (circuit No. 6).

There is a considerable number of differences in the design of the two lines. The following is mainly a description of the new line, though wherever there is an essential difference, it is pointed out.

Towers. The towers are galvanized steel towers, designed for six power cables and two ground cables (on the old line only one ground cable); they are spaced about ten to a mile and the cables on the new line are anchored at every fifth tower at least. All the towers on the new line are set in concrete foundations, while on the older line, steel tripod foundation stubs were used for the suspension towers.

The height of the tower is 44 ft., from ground to the lower crossarm. Ten and twenty ft. extensions have been used to increase the height of the towers whenever needed. The distance between the crossarms is 9 ft., against 7 ft. on the older tower line, and the ground wires are located 4½ ft. above the upper crossarm. Contrary to what was the case on line No. 12, where the power cables for each circuit were located all three in a vertical line one above the other, the cables on the new line have been staggered, so that the ground wire crossarm and the middle crossarm are the longest (each 23 ft. from tip to tip). The corresponding distance on the upper crossarm is 15 ft. and on the lower 17 ft. 6 in. This has been done to prevent trouble from sleet.

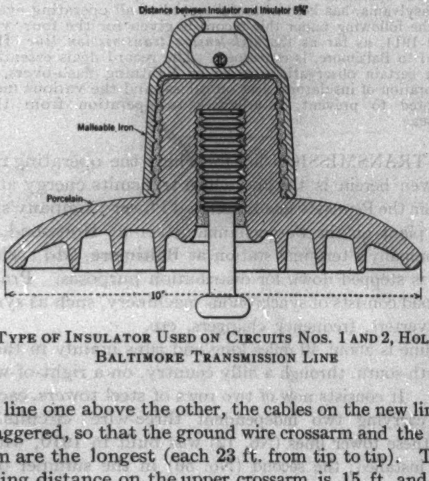


FIG. 3—TYPE OF INSULATOR USED ON CIRCUITS NOS. 1 AND 2, HOLTWOOD-BALTIMORE TRANSMISSION LINE

Conductors. The conductors are 300,000-cir. mil, 19-strand aluminum cable.

The ground wires consist of ⅜-in. galvanized seven-strand steel cable.

Calculated Load. Maximum load on the cables is assumed to occur at a temperature of 25 deg. cent., with a wind pressure of 15 lb. per sq. in. on wires covered with ½ in. of sleet. During

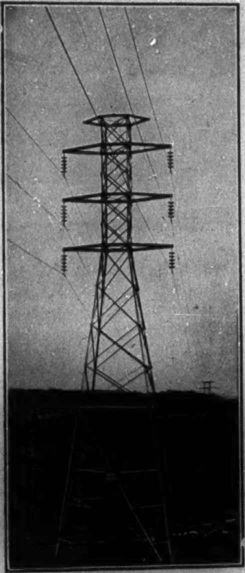


Fig. 1—Suspension Tower on Line 12—Holtwood—Baltimore

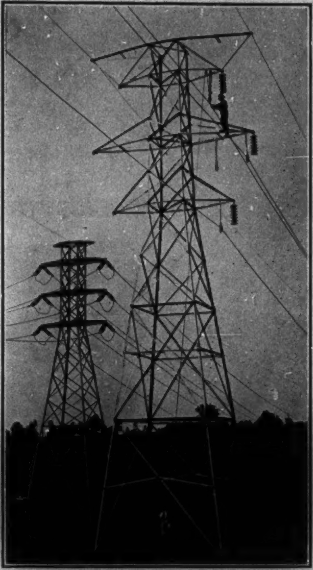


Fig. 2—Suspension Tower on Line 56—Holtwood-Baltimore—In the Background: Strain Tower of the Older Line No. 12

[BANG]

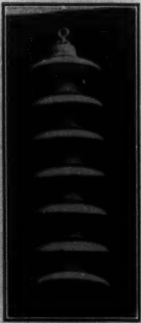
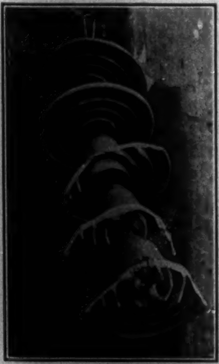


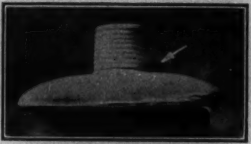
Fig. 5—String of Suspension Insulators for Line 56



[BANG]

Fig. 6—Partial Interruption No. 12, 1913. Insulator Removed from Tower No. 128, Bottom Phase, Circuit No. 2 Suspension Type

FIG. 7 [BANG]



[BANG]

FIG. 12—REMOVED FROM STRAIN TOWER NO. 163, 40,000 OHMS BETWEEN CAP AND PIN—BROKE DOWN AT 21,750 VOLTS—CRACK AT THE BOTTOM OF THE CAP

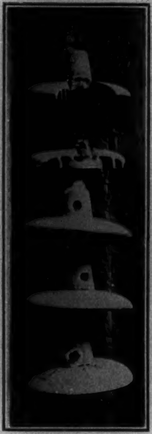


FIG. 10—INSULATOR STRING PUNCTURED ON LINE

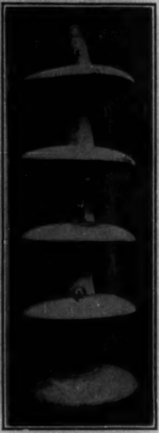
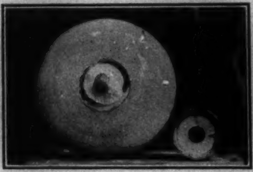
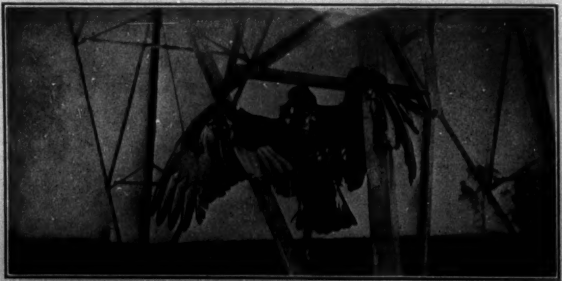


FIG. 11—INSULATOR STRING PUNCTURED BY TEST



[BANG]

FIG. 13—INSULATOR PULLED APART REMOVED FROM STRAIN TOWER NO. 34 CIRCUIT NO. 1, UNIT NO. 3 MIDDLE NORTH READ 50,000 OHMS



[BANG]

FIG. 14—TURKEY-BUZZARD KILLED ON LINE. NOTE SPECIALLY THAT LEFT WING IS BURNED

Dimensions—Tip of wing to tip of wing 65 in.—tip of wing to toe 34 in.—toe to beak 22½ in.

these load conditions the tension in the cables approaches the elastic limit.

The stringing tension at + 25 deg. cent., was 500 lb. for the power cables and 950 lb. for the ground cables.

Insulators. The insulators are of the suspension disk type, 10 in. in diameter. The units selected for the newer line have the following electrical characteristics:

Individual dry flash-over voltage = 95,000 volts.
Individual puncture voltage = 140,000 to 150,000 volts.
Units on older line have a dry
flash-over = 90,000 volts.
and puncture = 100,000 to 107,000 volts.

Eight units to the string are used on anchor towers and seven on suspension towers. Seven units correspond to a dry flash-over voltage of 378,000 volts.

On the old line originally, five and six units, respectively, were used for suspension and strain towers.

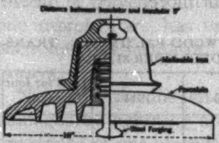


FIG. 4—SHOWING TYPE OF INSULATOR USED ON CIRCUITS NOS. 5 AND 6

The new tower line is built parallel to line No. 12, distance between lines being only 50 ft. on centers. On account of this it was necessary to place the towers on the new line as nearly as possible opposite the towers on the old line. The number of anchor towers has been increased on the new line in order to prevent longitudinal vibrations and to lessen the chances of sleet trouble.

The standard span is 500 ft., the shortest span is 125 ft., and the longest built with standard towers and cables is 1080 ft. All spans of 800 ft., or more are anchored at both ends. Double strings of insulators are used at all railroad crossings. The elevation of the line varies from about 600 ft. above sea level at the generating end to about 50 ft. at the receiving end.

Electrical Data.

Frequency.................... 25 cycles.
Normal line voltage between phases.................... 60,000 to 70,000 volts.
Ohmic resistance of one wire..... = 12.1 ohms (12 deg. cent.)
Ohmic reactance at 25 cycles is . . = 13.1 ohms
Impedance at 25 cycles is....... = 17.9 ohms

Losses in three lines at 200 amperes...................... = 5,800 kw. or 10 per cent when 58,000 kw. are transmitted.
Capacity current............. = 3.5 amperes per wire.

OPERATING RECORD

Below is given a tabulation of all the disturbances to normal operation of the system originating in the transmission lines, together with the cause of the trouble and the year it occurred. These disturbances have further been divided into three groups, depending on their seriousness, *i. e.*, total interruptions (T.I.), where all the load was lost, though generally not more than for a few minutes; partial interruptions (P.I.), where a percentage of the load was momentarily lost; and, finally, mere voltage or frequency disturbances (V.D.), where no load whatever was lost. These disturbances have been recorded whenever the voltage changed suddenly five per cent or more.

TABLE I.—OPERATING RECORD FOR HOLTWOOD-BALTIMORE TRANSMISSION LINE, JANUARY 1, 1911, to DECEMBER 31, 1914

Cause	1911			1912			1913			1914			Total for four years		
	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.	T.I.	P.I.	V.D.
Lightning.......	23	..	10	3	19	4	3	17	11	1	6	7	30	42	32
Defective insulators..........	..	..	..	..	..	..	1	..	..	..	1	1	1	1	1
Sleet on cables....	..	..	..	..	..	..	..	..	..	2	2	.	2	2	..
Birds on line.....	1	..	..	..	..	..	1	..	2	1	3	2	3	3	4
Wires blowing together.........	..	..	..	..	..	..	..	..	..	..	..	1	..	..	1

It will be seen that the cause for all the disturbances can be covered under the five headings: lightning, defective insulators, sleet on cables, birds on line, and wires blowing together.

Of these the overwhelming cause of trouble is lightning.

It may be of interest to recount a few observations made on the effect lightning has on a transmission line in operation.

Though the lines are protected at both ends with aluminum lightning arresters, which duly discharge during storms, lightning discharges or surges will nevertheless give rise to "flash-overs" on the line, which, once established, are maintained by the power from the generators. Such flash-overs practically always start at the towers where the clearance distances to ground (*i.e.*, tower structure) are the smallest (a double or triple ground to the same tower is naturally in effect the same as a two- and three-wire short-circuit). The path of the flash-over may vary. Thus, when circuits Nos. 1 and 2 originally went into service, the suspension towers were equipped with five units to the string and strain towers with six units. With this arrangement it was always found that the flash-over would occur upwards from the conductor, ***alongside*** the string of insulators.

Fig. 6 shows a typical string of insulators, damaged by such an arc. It can be seen how the three lower insulators are completely broken to pieces, probably mainly due to the heat generated by the arc; the bottom bolt shows a deep burn. It can also be seen from the marks on the string how the arc in this string, instead of traveling all the way from conductor to the tower in one unbroken arc, has broken into small individual arcs, each encircling one insulator. That happens frequently, though not always.

Not only the insulators but also the cable is liable to be damaged by lightning arcs; Fig. 7 shows a typical case. If the arc stayed at one place it would quickly burn the cable through. Fortunately, the arc is generally on the move. As a rule it is blown away from the power house, due to its own magnetic action. On the Baltimore transmission line we therefore generally find the cable damage to the south of the towers; traveling this way the arc burns and pits the cable in spots. In a few seconds the arc may travel five to thirty feet.

When it was found in the first lightning season (1911) that practically all flash-overs occurred along the insulators, the plan was tried in 1912 of increasing the number of disks of a suspension string to seven and of a dead-end tower to eight, on two particular stretches where the lightning had been especially severe. This proved successful in so far that only one lightning stroke occurred on these stretches in 1912 against 22 in 1911. Before the lightning season of 1913 one whole circuit (No. 1) was therefore equipped in this way with seven suspension and eight strain units. The result was, as shown by the power house ground chart record, that in 1913 the lightning flash-overs were distributed between the two circuits as follows:

27 lightning strokes on circuit No. 1.
20 " " " " " 2.
6 " " unknown on which circuit.

In other words, the circuit with the many insulators showed the larger number of lightning strokes. Evidence from inspection of the line showed, however, that whenever the flash-over took place on a suspension tower (which generally was the case in preference to a strain tower) the lightning arc on No. 2 circuit with the five insulators in the string, would as usual rise upwards along the insulator strings to the crossarm above, while on No. 1 circuit with the seven units in the string the arc would in every case go just the opposite way, *i. e.*, from the conductor to the crossarm below (see Fig. 8). This was naturally due to the fact that this clearance distance for the two upper conductors was materially decreased (from about 36 in. to 24 in.) by adding two more units to the string. For the bottom conductor, where the clearance distance still remained ample, the number of flash-overs was greatly reduced. This change in the location of the arc resulted in two distinct gains. In the first place, the arc did not have nearly the same chance for damaging the insulators by heat, as it did not pass alongside them but away from them. The insulator record for 1913 showed this clearly. Thus it was necessary to remove 210 insulators from circuit No. 2, due to lightning damage, and only three from No. 1 circuit. The other advantage gained was that it proved to be easier to extinguish the arcs on No. 1 circuit and that it could be done with much less loss of the synchronous load connected to the system (on account of the preponderance of two-wire short circuits compared with three-wire short circuits). The following year one more unit was added to No. 2 circuit suspension towers and two more to the strain towers, and this is the way it is at present.

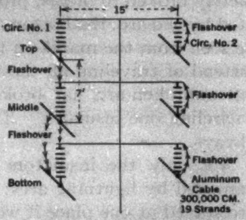


FIG. 8—DIFFERENT PATHS TAKEN BY LIGHTNING FLASH-OVERS

Altogether the number of insulators removed from the line due to lightning damage is small, not more than about one hundred per year, on the average, and the number is not on the increase.

Far more important from a maintenance point of view is the continuous *deterioration* of the porcelain in the insulators, such as it was discovered a few years ago could be determined on insulators of the suspension type by means of taking insulation readings between the pin and cap (megger tests).

The Pennsylvania Water and Power Company began investigations by this method in the autumn of 1913. The megger used was a 1000-volt instrument with a range from 10 to 2000 megohms. The result was rather surprising. While the majority of insulators, when the weather was dry enough to permit of any testing, naturally would read infinity, many were found which would read below the scale of the instrument, *i. e.*, below 10 megohms. When these were tested later on with a lower-reading megger, many of them would read even below ½ megohm or lower. On none of them could any external damage be seen. To all outside appearances they were perfectly good insulators and still their insulation value was gone.

The first complete test of circuits Nos. 1 and 2 was made in the winter 1913-1914, after about three years of operation. Counting as bad every unit which would give a megger reading below 500 megohms, this test showed that out of about 22,400 units, 1621 or 7.3 per cent were found to have deteriorated.

The same line was gone over again in the autumn of 1914, about half a year after the first test, and showed an additional number of about 1020 or 4.7 per cent which had gone bad. This indicates clearly how rapidly this deterioration process is going on. All told, four years' operation produced 2640 bad units, or 11.7 per cent, an average of 2.9 per cent per year. Judging from the last test, it seems as though this deterioration goes on at a rapidly increasing rate year after year.

Table II shows the result from both tests combined, but gives the figures for strain and suspension towers and for the two circuits separately. It will be seen that the two circuits have practically the same number of bad units, but the strain towers on both circuits show a very much larger percentage (17.1 per cent) of damaged units than the suspension units (7.6 per cent), indicating that the horizontal strain units are very much more exposed to this trouble than the vertical suspension units.

A number of other tabulations have also been made up to see if there were any difference between insulators from the top, middle and bottom phases, or between the various units in a string. Only slight differences could be found, excepting between the different insulators in a suspension string. Taking only the five first insulators in the string, which have been in service from the beginning of operation, we find that the top unit, *i. e.*, the one nearest to the crossarm, is the one most subject to damage. (See Table III).

After a number of these units were removed from the line, a series of tests was made in an attempt to determine the cause of this trouble. The tests were as follows:

First: 230 units with megger readings from 0.01 to 500 megohms were given a high-potential test (25 cycles). All of these units punctured before flash-over voltage, the puncture voltage varying widely, increasing in a general way, however, with an increased megger reading. Fig. 9 shows an attempt to express this relation in a curve. It will be seen that while a very low reading insulator will puncture at less than 20,000 volts, an insulator giving a megger reading above 300 megohms has a puncture voltage close to the flash-over point. This puncture takes place inside through the porcelain hidden between the pin and the cap. By continuing the current from the testing transformer until the puncture heated up, it could be felt, on the outside of the cap, that the breakdown generally took place on the side and very often close to the rim of the cap.

TABLE II

NUMBER OF INSULATORS DETERIORATED ON PENNSYLVANIA WATER AND POWER COMPANY'S CIRCUITS NOS. 1 AND 2, 1911-1914

Circuits	Strain insulators		Per cent damaged	Suspension insulators		
	Units tested	Units below 500 megohms		Units tested	Units below 500 megohms	Per cent damaged
No. 1	4,938	856	17.3	6,723	470	7.0
No. 2	4,942	832	16.8	5,900	485	8.2
Nos. 1 & 2	9,880	1,688	17.1	12,623	955	7.6

TABLE III

SUSPENSION INSULATORS NOS. 1-5 DETERIORATED 1911-1914

Unit No.	1	2	3	4	5
Circuits Nos. 1 and 2........	210	120	142	169	146

Second: While these tests were going on, a puncture of each and every one of a string of five insulators occurred one day on the line, during actual operation. No lightning was reported, the weather was clear and no switching was done at the time of the disturbance. Fig. 10 shows this string. It can be seen that holes as large as a finger tip are burned through the porcelain and the cap, all on the side of the insulator, thus forming a short path between the pins and caps; no evidence of any simultaneous flash-over could be seen. It was a case of a clear puncture.

It was naturally thought that this was a case of deteriorated porcelain, which could have been caught in time to prevent failure, if only megger readings had been taken of these insulators some time beforehand. To prove this, five units removed from the line because of low megger readings were mounted in a string and high voltage was built up on them, not from a testing transformer, where the short-circuit current always is small, but from a 70,000-volt, 10,000-kw. transformer, with a 10,000-kw. generator behind it. The current was limited to about 250 amperes by a resistance.

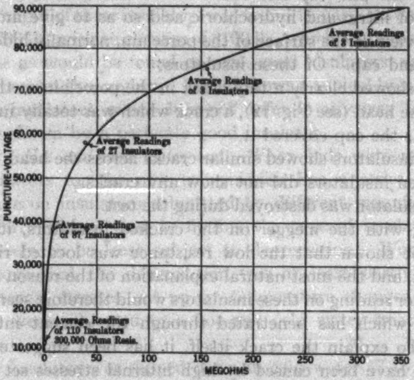


FIG. 9—RELATION BETWEEN MEGOHMS AND PUNCTURE VOLTAGE OF 230 INSULATORS TAKEN FROM THE BALTIMORE TRANSMISSION LINE IN THE EARLY PART OF 1914.

The result of this test is shown in Fig. 11; when the voltage reached about 30,000 volts, the insulator punctured, and burning porcelain and iron was, so to speak, shot out from the side of first one, then of another insulator, leaving holes of just the same nature as found in the insulator string punctured on the line. (That the bottom insulator does not show any hole but only a "hot" spot is simply due to the fact that the current was taken off too early.)

Third: While the foregoing tests conclusively prove the serious nature of this insulator deterioration, they do not throw much light on the real nature and the cause of this trouble. The following tests were made with this object in view.

On 24 insulators discarded from the line because of low megger readings, the pin, cap and cement were dissolved in a diluted solution of nitric and hydrochloric acid so as to give an unobstructed view of the surface of the porcelain, normally hidden by the pin and cap. Of these insulators:

Seven showed clearly a tiny crack in the porcelain at the bottom of the head (see Fig. 12), a crack which was totally invisible as long as the cap covered it.

Three insulators showed similar cracks across the head.

Thirteen insulators did not show any cracks.

One insulator was destroyed during the test.

Trying with the megger on the cracked insulators, it could readily be shown that the low resistance was located right in the crack, and the most natural explanation of the reason for the low megger reading on these insulators would therefore seem to be moisture which has penetrated through the cement into this crack. To explain the crack itself, it has been suggested that this may have been caused by high internal stresses set up by uneven temperatures and expansion of the various parts in the insulator, which would be likely to occur, for instance, if the insulator becomes hot in the sun and is then suddenly cooled by rain. A. O. Austin has also suggested that crystalline growth in the cement may cause expansion of this, with consequent heavy stresses in the porcelain.

None of these explanations would seem to hold good for the insulators where no cracks could be found. On these insulators it was possible, however, by means of the megger, to trace areas of low resistance on the outside of the insulator head. . It seems evident, therefore, that the acid used in dissolving the pin and cap had penetrated the unglazed body of porcelain between the pin and cap in spots, thus making it more or less conductive. But wherever acid can penetrate porcelain, it is natural to suspect that plain water can do the same. It is therefore believed that the failure of these insulators is due to ***porous material or lack of vitrification in the burning***, which gradually has allowed moisture to be absorbed by the porcelain in the same way as moisture has penetrated through the cracks in the cracked insulator.

Fourth: When it was first discovered that a large percentage of the low megger readings was due to cracks in the porcelain, it was naturally feared that these insulators had lost a great part of their mechanical strength. This proved, however, not to be the case. Twenty-five were picked out at random and tested in a pulling machine until mechanical failure. The ultimate strength of these insulators was found to vary between 6500 and 10,700 lb., with an average of 8100 lb., which is approximately the same as would be found on new, good insulators, when the cement had set thoroughly. Fig. 13 shows a typical break of one of these insulators, which does not differ in any way from the fracture shown by a perfectly good insulator.

Fifth: Hot and cold water test. When bids were requested for insulators for the new transmission line a series of tests was made on insulators submitted by different manufacturers, particularly with a view to finding the type of insulator that would seem to be least subject to depreciation. Working on the theory that the depreciation was at least partly due to high internal stresses, set up by temperature changes, the insulators were subjected to a hot and cold water treatment as follows:

Each insulator was dipped down in cold water (7 to 8.5 deg. cent.) and left there until thoroughly cooled (5 minutes); it was then taken up and within two or three seconds lowered into boiling water, head first. After remaining there for about five minutes, it was given a second temperature change by transferring it back into cold water, and so on. After each temperature change the insulator was tested with a megger and discarded if it gave a reading less than "infinity." If an insulator endured the treatment without any change in resistance it received in all 10 temperature changes. Table IV shows the result for six different types of insulators, designated A to F.

The insulators which had not been damaged by the hot and cold water test, so far as could be determined by the megger, were now subjected to high potential, with the results as shown in Table V.

TABLE IV

	Type	Weight per unit	Number of insulators		No. of single temperature changes withstood by insulators	Number of insulators that failed when transferred from	
			tested	failed		cold to hot	hot to cold
	A	8.5 lb.	19	6	141	3	2
	B	9 "	19	12	104	5	7
	C	10 "	19	12	88	4	8
	D	9.5 "	19	16	67	1	15
	E	11 "	6	0	60		
	F	11 "	6	2	40	2	

TABLE V

Type	Total No. insulators tested	No. units which withstood flash-over	Number of units punctured and puncture voltage
A	13	6 (92 k.v)	7 (43 to 91 kv.)
B	7	3 (96 k.v)	4 (50 to 95 kv.)
C	7	1 (90 k.v)	6 (27 to 87 kv.)
D	3	0	3 (38 to 70 kv.)
E	6	6 (98 kv.)	
F	4	4 (85 kv.)	

These tabulations show that type E insulators withstood the tests the best, as none of them failed, while types C and D suffered the most, for, among 38 insulators treated, only one withstood the flash-over voltage afterwards.

The insulators which had already shown up poorly on the megger test were also given a high-potential test. They all punctured at voltages varying from 18,000 to 24,000 volts. The megger reading before test varied from 0.4 to 9 megohms. The cap and pin were also dissolved on two of the damaged insulators of types D and F. Both showed tiny cracks at the bottom of the head.

Sixth: Drying out of the insulators. Working on the other hand on the theory that, at least in part, this insulator trouble was due to absorption of moisture without accompanying cracks, the plan was tried of drying out some of the insulators removed from the line, under high vacuum and at temperatures varying from 50 to 90 deg. cent. A primitive air-tight tank which could contain 12 insulators at a time in a row was installed, equipped with electrical heaters and connected to a vacuum pump, which would maintain a vacuum of about 27 in.

Altogether, three batches of a dozen insulators were dried out with this equipment. The drying out lasted from 10 to 20 days and megger readings were taken every few days. A graphic thermometer gave a continuous record of the temperature of the cap of one of the insulators.

The following observations were made:

A. After only a few hours' treatment, the insulation resistance decreases materially, probably because water is a better conductor when hot than when cold.* After 24 hours' treatment a material increase is, however, always found, and this continues steadily until many of them reach the infinity mark, even when hot. All of them, without exception, will record infinity, when tested cold after two days' treatment.

After drying out, the insulators were given a high-potential test with 25 cycles.

B. *The result was that out of a total of* 37 *insulators tested,* 12 *withstood a heavy flash-over test for ½ min.* The rest of them punctured at voltages varying from 30,000 to 90,000 volts. As the megger readings on some of the insulators that withstood the flash-over were as low as 1 to 2 megohms before drying out, there cannot be any doubt but that they would have punctured at low voltages if they had not been treated.

C. The insulators which dried out the quickest punctured at the lowest voltages. These presumably were the cracked insulators. On the other hand, the insulators that withstood the high voltage generally increased very slowly in insulation. These perhaps were insulators which would not have shown cracks under the cap.

D. Four of the successfully dried out insulators have since that time, *i.e.*, for four months, been exposed to the weather, hanging in a vertical position. They still read infinity. It is believed that if means could be found to prevent moisture from re-entering such insulators, it would be perfectly safe to put them out on the line again.

It has often been suggested that the deterioration of insulators was due to electrical causes, such as switching, surges, arcing ground, high-frequency discharges, etc. As an indication that this is not the case, an insulator record from a 70,000-

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*For a more scientific explanation of this phenomenon, see a very interesting article on "The Characteristics of Insulation Resistance," by S. Evershed in the *Journal of the I. E. E.*, Vol. 52, No. 224.

volt transmission line between Holtwood and Lancaster, 13 miles long, may be of interest. This line was built in the summer of 1913. It consists of two identical circuits on the same tower line. While the two circuits were built at the same time, it has been customary to use only one of them, while the other one was kept as a spare. Both lines were gone over with a megger in the winter of 1914. At the end of the test one of the circuits had been under voltage 481 days, the other one only 91 days. Still they showed very nearly the same percentage of damaged units, *i.e.*, 8.9 per cent against 8 per cent.

It seems therefore clear that the influence of the voltage on the line in this respect is very small, if any.

On the whole, the insulator record given above, and the experiments made, all tend to show that the deterioration of the type of insulator in question is not due to electrical but rather to mechanical and ceramic causes.

Sleet. On the operating record, Table I, we find "sleet" next on the list.

It is now well understood that the most common cause of sleet trouble is the fact that when, with the arrival of milder weather, the sleet starts falling off the wires, it will often fall off one full span or several spans at one time but still remain on other spans. Such conditions result in unequal loading and therefore also extremely unequal sag for the different spans. If the wires of different phases, therefore, as on circuits Nos. 1 and 2, are in the same vertical plane, they are liable to come in touch with each other and produce short circuits. The few disturbances recorded as caused by sleet on the Baltimore transmission line have all been of this nature.

In building the new line to Baltimore it has been attempted to prevent or minimize this trouble by having the middle crossarm extend farther out (about 2 to 3 ft.) than the top and bottom one; a larger number of strain towers has also been used, so as to avoid having more than five suspension spans between two dead-end towers. It may be of interest to note that during a recent sleet storm where both the old circuits, Nos. 1 and 2, were short-circuited, due to sleet, the new one, No. 6, stood up without a single short circuit.

There is, however, another method of preventing sleet trouble, which the Pennsylvania Water and Power Company lately has adopted. The principle of this method is simply to keep the transmission lines so hot that no sleet whatever can be formed on them. The heat is produced by circulating electric current through the wires. Test and experience show that for a 300,000-cir. mil aluminum cable, about 250 to 300 amperes is enough to keep the sleet from sticking to the cables; often even less current will do it. On the other hand, if ice already deposited on the wires is to be melted off, considerably more current is necessary. The present arrangement, when a sleet storm is reported and the load is at its lightest, is to leave only one circuit in service, which carries all the load (No. 6), while the two others are connected in series, short-circuited at one end and current is sent through them from two generators and two transformers.

If the load is heavier, all three circuits will be put in service, and if the current is not judged to be sufficient to prevent sleet, an arrangement is adopted by means of which wattless current is brought to circulate over the wires while they at the same time carry the load. This purpose is gained by dividing the generators at the power house into three groups, each of which through its respective transformers is connected with one transmission circuit. The three circuits are paralleled at the substation end. The field is now kept *open* on the generators for one of these groups, while the others are over-excited. Consequently the generators with the open field will draw their excitation from the a-c. side, but this current will first have to pass the transmission line. An increase of from 40 to 200 per cent in total current for the three lines, depending on the load conditions, can be secured this way. A limit is set by the current-carrying capacity of the station equipment.

Buzzards. Fourth on the list of disturbances we find the heading "birds on line." The birds troubling this line are turkey buzzards. These birds often choose the towers as a resting place and here they are liable to ground the line to the tower through their own bodies. There is especial danger if they sit on the crossarm right below the live wire, particularly in the case of the suspension towers of circuits Nos. 1 and 2, where two extra units have been added; the clearance here is so small (only 24 in.) that even a small buzzard, the moment it starts to fly away, easily will reach the line overhead with the tip of its wing, while it still touches the tower with its feet. A buzzard grounded in this way is always killed and will generally drop down to the foot of the tower where it afterwards can be found. Fig. 14 shows a good-sized sample. (Toe to beak 22½ in., tip to tip of wings 65 in., tip of wing to toe 34 in.). Often they will fall down without even causing a voltage disturbance, but frequently they will give rise to an arcing ground, which may even develop into a two-wire short circuit.

On the new line (circuits Nos. 5 and 6) the minimum clearance from wire to ground is 47 in., so it is hoped that this line will prove "buzzard-proof."

Wires Blowing Together. The one voltage disturbance recorded as being due to this cause, represents a case where the ground wire swung into one of the power cables at a place, on a special tower, where the clearance distance was abnormally small. It is therefore of no special interest.

PROTECTIVE DEVICES

Let us review the transmission line troubles:

They were caused by:

1. Lightning.
2. Defective insulators.
3. Sleet.
4. Buzzards.
5. Wires blowing together.

It has been described how the company has tried to maintain and improve its lines and operating methods so as to avoid, as far as possible, trouble from the above causes. In order to maintain continuous operation, also, when grounds or short circuits, due to any of the above causes, occur on the line, several different protective devices have been adopted, which are briefly described below:

1. *Interlocking Line Relay.* Trouble from defective insulators, sleet, buzzards, and the wind swinging the wires together, generally, if they give any trouble whatsoever, result in grounds or short circuits that persist on the system until the voltage is taken off the faulty line; sometimes it may even result in a permanent fault, that does not permit restoration of voltage until repairs are made. The natural method to safe-guard operation against such troubles is therefore to cut the damaged line out, and the earlier the better. This means, as a general scheme, automatic operation of switches.

The system in use is illustrated in Fig. 16. It consists simply of overload relays at the power house connected in series with the line current transformers and also one relay in the ground connection for the neutral of each transformer bank. At the substation, reverse-current relays take the place of the overload relays at the power house. All these relays are themselves made as instantaneous in their action as possible, but they do not act directly on the trip circuit of their respective oil switches, but are used in connection with definite time limit relays set for various time elements ($\frac{3}{4}$ to 3 seconds) so that a momentary short circuit will not produce action. To prevent all three lines from going out by relay action, in case there should be a short circuit on all the lines at the same time, the trip circuits are interlocked.

This system has, with various minor changes, been used since the starting of the plant. It has not always been entirely successful. Difficulties were especially encountered in giving the various relays a suitable current and time setting, and due to the complication in wiring introduced, since low-tension automatic switching was adopted. Since June, 1914, when various changes were made, especially on the reverse-current relays, so that they would be more sensitive, the record shows seven entirely successful actions, out of a total of nine times when the conditions were such that they could act correctly.

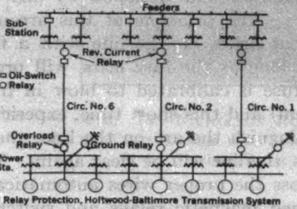


FIG. 16—SIMPLIFIED DIAGRAM OF TRANSMISSION SYSTEM, SHOWING LOCATION OF LINE RELAYS

It may be asked why the same interlocking relay arrangement is not sufficient as lightning protection. The reason is the simple fact that lightning flash-overs very often will occur on both circuits Nos. 1 and 2 at the same time. (It still remains to be seen whether they will occur on all three circuits at the same time.) When both circuits are in trouble at the same time, the clearing of both means, of course, a total interruption.

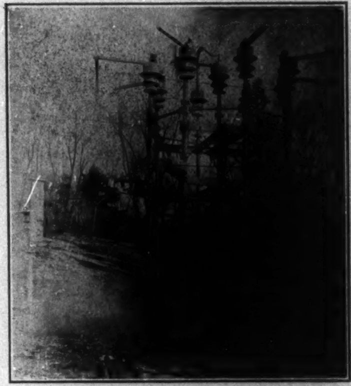
Even during the first year's lightning season it was noticed that though the lightning short circuits were so severe that it was necessary to clear the circuits, the insulators and cables were never so badly damaged that it was impossible to come right back with the voltage, right after the interruption. This indicated clearly that if only some means could be found to extinguish the power arcs, an interruption might be avoided.

The first scheme tried with this end in view was based on the idea of clearing one line completely, by means of the high-tension oil switches at both ends, while the other one, even if in trouble, was supposed to maintain some kind of synchronism with the customers' load; then immediately, *i.e.*, as fast as the oil switches could do it, the first circuit would be put right back again and the second line cleared, etc. The system was actuated by overload relays at Holtwood and their action was transmitted by means of overhead wires to other relays at the substation, so as to get synchronous action of the oil switches. This system proved a failure mainly because it was found that certain atmospheric conditions of no danger to the high-tension transmission lines, would produce discharges through the overload relay wires and thus unnecessarily actuate the relays at the substation and trip the oil switches. The system was therefore soon discarded.

The next system adopted, which is still in use, was the arc extinguisher arrangement invented and designed by Mr. L. C. Nicholson, Buffalo, N. Y. The principle of this arrangement is to shunt any arc that arises on the line with a fuse wire, so that the current, as long as the fuse lasts, will prefer this path to the arc. The fuse is calibrated to blow in from 5 to 10 cycles (25-cycle system) and this short time, experience has proved, is enough to extinguish the arc on the line; therefore as soon as the fuse blows, the line will be clear again. The fuse wires are connected across the proper wires automatically by means of specially designed magnetic relays and switches. The whole arrangement is placed right outside the power house. The design of the equipment is such that seldom more than one cycle will pass from the time the lightning arc is established until the switch is closed. It is in this speed that the apparatus has its greatest advantage, since it allows the arc on the line so very little time to spread and do damage.

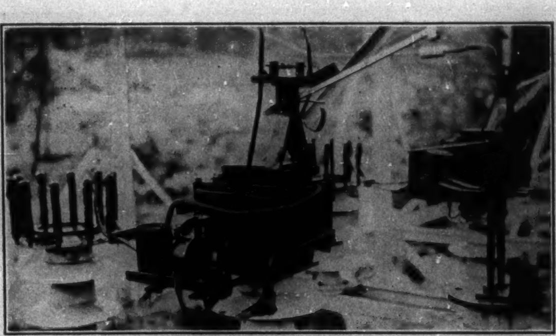
An important point for successful operation is to have the fuses timed correctly. If this time is too short the arc may be re-established, and if too long, it is very difficult for the synchronous load to remain in synchronism. The size of the fuse to use was originally determined by test. As a check against values found this way, cycle recorders are also installed between the fuse banks, so that an actual record of the time it takes a fuse to blow, during a lightning storm, always can be found afterwards.

Figs. 20A and 20B are two oscillograms which illustrate the action the short-circuiting of the lines with such fuses has on the system. One oscillograph was mounted at the power house



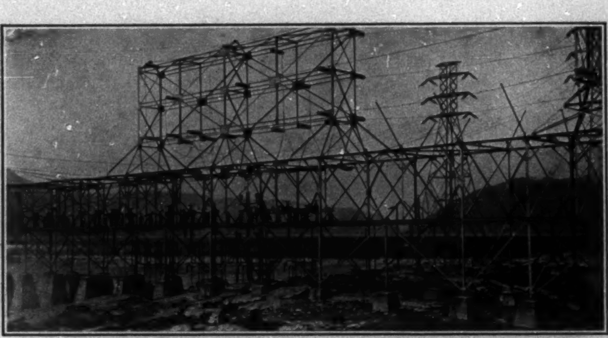
[BANG]

FIG. 18—NICHOLSON ROTARY FUSE BANK. THE PHOTOGRAPH WAS TAKEN AT THE INSTANT THE FUSE BLEW



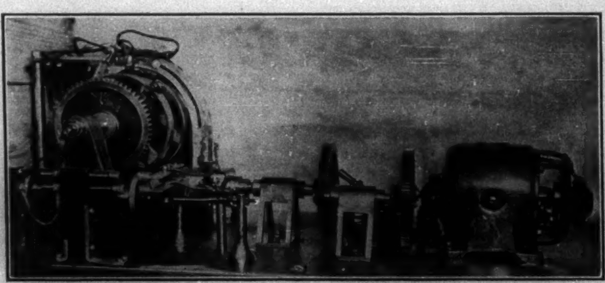
[BANG]

FIG. 18—NICHOLSON MAGNETIC SWITCH AND RELAY



[BANG]

FIG. 19—GENERAL ARRANGEMENT OF NICHOLSON ARC EXTINGUISHER SHOWING STRUCTURE FOR LOCATION OF RELAYS AND IN THE BACKGROUND A SET OF ROTARY FUSE BANKS



[BANG]

FIG. 21—RELAY MOTOR AND REVOLVING DRUM FOR RICKETTS FIELD—DESTROYING AND RESTORING DEVICE

and one at the substation. On both oscillograms the two outer curves represent the low-tension bus voltage, while the middle wave represents the high-tension line current. The short circuit was a three-phase one made with No. 16 B. and S copper wire. Two generators of 10,000 kw. capacity were feeding a synchronous load of seven 1000-kw. synchronous converters over one line. It will be seen that the fuse blew in 5½ cycles.

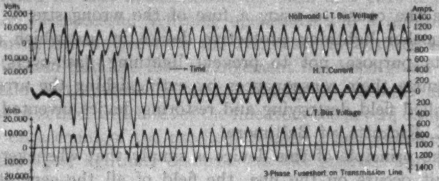


FIG. 20A—THREE-PHASE FUSE SHORT CIRCUIT ON TRANSMISSION LINE

The middle wave represents the high-tension current, the others the low-tension bus voltage at the power house.

As the relays work on the principle of overload, the fuses are now only put in service when a lightning storm is reported. Otherwise it can not be prevented that fuses unnecessarily will blow and thus introduce undesirable complications when short circuits occur on the low-tension system, and on other occasions when their action cannot possibly be of any benefit.

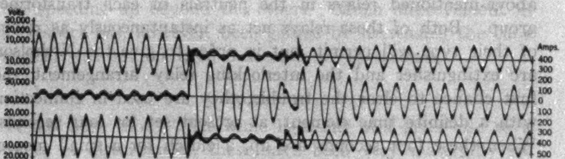


FIG. 20B—SAME AS FIG. 20A

The middle wave represents the high-tension current at the substation, the two outer ones the low-tension bus voltage at the substation.

This device is especially satisfactory on the Baltimore line when only a ground or two-wire short circuit occurs. In such cases it saves all or practically all the synchronous load. On three-phase short circuits the action is more severe, but generally about 50 per cent of the load can be saved, especially if the synchronous converters of the connected load are separately excited or by other means prevented from reversing polarity. By keeping the voltage on the line all the time it makes it also possible to restore lost load more quickly than otherwise would be the case. In 1913 and 1914 it cleared the line successfully a total number of 25 times out of 40 times the lightning hit the line. Wherever it has failed it has generally been possible to trace the cause to using a fuse of the wrong size.

Another lightning protective device in use which also has as its purpose, not to prevent lightning flash-overs, but to minimize their consequences by extinguishing the arcs, is the so-called field destroying and restoring device invented by Mr. F. E. Ricketts, of Baltimore.

The principle of this device is simply that whenever a short circuit occurs on the line, the field of all the generators will for a moment be destroyed, so as to allow the arc on the line to be extinguished on account of lack of voltage, and then immediately after be built up again so as to force the synchronous load into step again before the synchronous converters, frequency changers, etc., have come to a stop. The necessary switching for operating this device is naturally done automatically.

The actuating relays are in this case either an overload relay (of the ordinary plunger type) in the generator circuit, or the above-mentioned relays in the neutrals of each transformer group. Both of these relays act as instantaneously as relays of their type will permit, but in order to give the Nicholson arc extinguisher and the interlocking relay arrangement the first chance to clear the trouble, they are used in connection with a definite time element, at present set for four seconds. When these four seconds are up, a clutch for a small motor, which is running continually, will be thrown in contact and start a drum rotating. On this drum contacts are arranged so that as soon as it starts all the ordinary field circuit breakers (one for each generator,) will be opened simultaneously, at the same time short-circuiting the field windings across their respective discharge resistances, thus allowing the field gradually to die out and the line voltage to be reduced correspondingly. Meanwhile the drum continues to revolve and will, after a predetermined time (originally 5 sec., now 1½ sec.), close other contacts which have the effect of slamming all the circuit breakers in again. Immediately the fields and line voltage start to build up again. After some surging between the generators themselves individually and the generator and synchronous load, the voltage will again be normal, generally after about one minute. The drum continues to rotate until it has made one complete revolution, after which time it is disengaged from the motor and the whole equipment ready for another operation.

The record for this device shows for 1913 and 1914 a total number of 12 successful lightning operations and 4 failures.

Comparing this device with the Nicholson arc extinguisher, it must be said that the fuse arrangement has been given preference and first chance for acting, mainly on account of its quickness of action, which saves the line from too severe damage, and also on account of the excellent results it has produced in case of the lesser lightning disturbances like grounds and two-wire short circuits.

The field-destroying device treats all lightning disturbances as equally severe and produces the same disturbance on practically all of them, but seems, on the other hand, to have the great advantage of extinguishing the arcs with more certainty.

Difficulties with this device can mainly be traced back to the waterwheel governors. It is especially difficult when the synchronizing power between the generators themselves for a moment is lost with the field, to prevent a generator whose prime mover is on hand control (*i.e.*, has a steady gate opening), from speeding up beyond the others. Much improvement in this respect has, however, been gained by decreasing the time the field was left off from 5 seconds to 1½ seconds.

CONCLUSION

It has been shown that while lightning still gives rise to a number of disturbances, these have been very materially reduced both in number and in severity, year for year, by the use of special protective devices. As to sleet, special operating methods have been adopted during such storms, which it is believed will prevent trouble from this cause. The approaching danger from deterioration of the insulators has been discovered at an early stage, and rigid and repeated elimination tests of bad insulators, with megger, have been adopted as part of the routine maintenance, so that it is felt that *operation* will have but little to fear from this source.

DISCUSSION ON "FOUNDATIONS FOR TRANSMISSION LINE TOWERS AND TOWER ERECTION" (WALLS, LEEPER, MITCHELL, DOWNING, CONNERY), AND "FOUR YEARS' OPERATING EXPERIENCE ON A HIGH-TENSION TRANSMISSION LINE" (BANG), DEER PARK, MD., JUNE 29, 1915.

R. J. McClelland: As a large part of the transmission line tower failures in the past have been due to weakness in the foundations or footings, rather than in the towers themselves, the topic under discussion is a pertinent one. Lack of complete information on the behavior of tower foundations in different soils has doubtless been largely responsible for such unsuitable designs and methods as have been employed, and transmission line engineers have come to an appreciation of the need of thorough acquaintance with the soil conditions with which they have to deal in any given case. This has led to making not only test pits along the route, but to conducting tests on sample foundations in place at different points.

It may be of interest to show some results of tests which were carried out for this purpose in designing the tower foundations for the 130 kv. line between Grace, Idaho, and Salt Lake City, which was built in 1913 for the Utah Power & Light Company. Various locations fairly representing the different soils were chosen, and steel and concrete foundations of different proposed types were set and tested for their holding power against vertical uplift, the movement under varying loads being recorded.

Figs. 1 and 2 will serve to illustrate the results secured from individual tests, while Fig. 3 gives a summary of the series of tests.

It is unfortunate that the available time did not allow a similar series of tests, for comparison, to be made upon duplicate foundations after allowing settlement of the backfill for several months or a year. As it is known that the holding power very materially increases during, at least, the first several months, the results obtained were regarded as a conservative representation of the ultimate conditions, and therefore safe as a guide in design.

One of the points brought out was that the upward movement of the foundations would, as a rule, become appreciable with a pull of approximately 2000 lb. per sq. ft. for backfilling which had stood 20 days. It was further noted that the uplift under these conditions would generally vary from ½ in. to 1 inch by the time the pull was equal to only one half of the weight of the 30 deg. earth cone which is ordinarily used to calculate the holding power of footings. The above, which tends to show that the bearing pressure of the upper surface of the grillage against the earth has considerable influence, especially beyond a depth of 3 or 4 feet, would indicate that attention should be given to providing sufficient area to keep the unit pressure at a moderate value. In these tests the bearing pressure, after continual movement had begun, varied from 1000 lb. per sq. ft. for freshly tamped wet backfills up to 4 and 5 tons for dry clay and gravel after having stood 20 days.

Test No. 2 shown in Fig. 3, exhibiting a very low value for uplift, was made in the old exposed bed of Great Salt Lake, where the soil was very wet and consisted of stratified clays which came out in lumps when excavated. During the tamping, the backfill became much of the consistency of putty because of the inability to keep the hole clear of water. The test made after two days showed that the footing would steadily pull up with force of less than 1000 lb. per sq. ft. without any movement whatever of the ground surface.

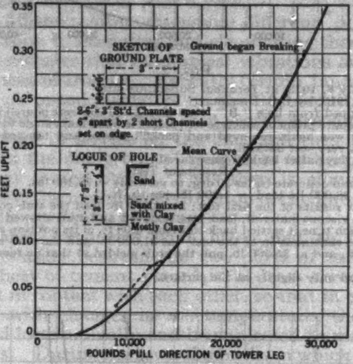


FIG. 1

Test made in Milliken open hearth building—reported May 13, 1913, by E. E. Moore—backfill carefully tamped—test made 20 hr. after hole was refilled.

Results of Test.

Pounds Pull	Ft. Uplift	
8,400	0.031	
12,000	0.073	
14,000	0.083	
16,000	0.109	
18,000	0.135	
20,000	0.167	
22,000	0.188	
24,000	0.224	
26,000	0.255	
28,000	0.302	Ground began
30,000	0.417	breaking and upheaving
31,000	0.521	

Further increase in load produced steady movement of anchor.
Wt. of cone of earth (sides 30 deg. to vertical) = 33,250 lb.
Earth pressure at 28,000 lb. load = 8800 lb. per sq. ft.
Grace Terminal transmission tower footing test—2 channel stub—earth fill.

Specific instances of footings displaced by not unduly heavy wind pressure upon towers and conductors within a short time after erection are not particularly rare, but after thorough settle-

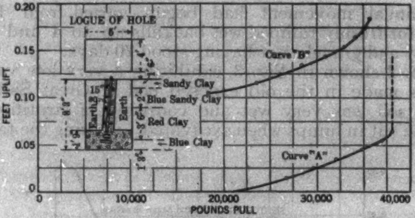


FIG. 2

Test was made July 8, 1913, at Terminal Substation site.
Reported July 12, 1913, by J. C. Damon.

The water was dipped from hole " B ", stub placed and concrete poured in to a depth of 1 ft. 9 in. A 15 in. square prism of concrete was placed around main angle to level of ground surface. The water was again removed and backfill placed and tamped—rapid inflow, however, produced a very wet backfill

Test was made 11 days after backfill was placed.

Results of Test.

Wt. of earth cone and concrete (sides 30 deg. to vertical) = 78,400 lbs.

Earth pressure at 38,000 lb. load = 1,900 lb. per sq. ft.

Curve A shows the results of the first test: at 38,000 lb. load the stub continued to rise as if coming through viscous material; load was removed and stub allowed to stand a few moments, during which time it settled back to within 0.08 ft. of its position at the start.

Curve B shows the continuation of the test—at 31,000 lb. pull the stub reached its previous uplift of 0.14 ft., and at 35,500 lb. pull the stub yielded so that no further force could be developed.

The ground cracked only slightly at the surface.

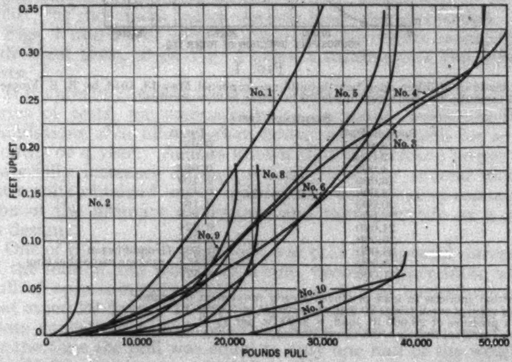


FIG. 3—CURVES SHOWING RELATION BETWEEN UPLIFT AND APPLIED PULL

Curve No.	Time Elapsing	Type of Stub	Backfill
1	1 day	2 channel A in earth	Dry, well tamped
2	2 days	2 " A " "	Wet and soft
3	2 days	2 " A " "	Dry, well tamped
4	1 day	2 " A " "	Dry, rocks tamped in hole 2½ ft.
5	1 hr.	2 " A " "	Dry, rocks tamped in hole
6	1 hr.	3 " A " "	Dry, no rocks used
7	11 days	B stub in concrete	Wet and soft clay
8	20 days	B " " "	Wet and soft quick-sand.
9	20 days	2 channel A in concrete	Wet and soft quick-sand.
10	27 days	3 " A " "	Dry, well tamped

ment the same footings have shown no movement whatever, even during the most severe wind storms. One such example is a case in Texas where a steel tower transmission line was erected during the early summer months when the soil was in a hard dry condition. The backfilling was carefully done, but when the fall rains came on, the hard lumps of earth softened up to such an extent as to flow around the grillage, allowing five of the towers to overturn during a wind storm. The backfilling did not become entirely firm for at least a year.

A. S. Mc Allister: After discussing different possible causes for deterioration in insulation and eleminating them one by one, Mr. Bang concludes that mechanical vibrations and defects are the main causes of trouble. Recently certain Japanese porcelain manufacturers tested insulators on the line simultaneously with insulators that had been kept in a storehouse during the time the others were in service on the line, and they found the deterioration in the one group of insulators to be practically the same as that in the other. Thus there is eliminated another cause, namely, the mechanical vibration of the line, which would not affect the insulators in storage.

The Japanese engineers have attempted to overcome the difficulty by using between the two parts of each insulator a very thin sheet of cement placed in at least three independent sections not in contact with each other, so that in expanding and contracting with changes in the temperature, the cement will be expanded longitudinally and be subjected to moderate transverse strains. During the several months in which the insulators have been in operation they have shown no deterioration.

E. E. F. Creighton: Mr. Bang's drying-out tests, I think, are extremely clever in the deduction he draws from them. He takes a number of insulators and dries them out and measures very carefully and systematically the increase in resistance from day to day, and he draws the conclusion that those that dry out first are the ones most badly cracked, which is quite evident when you think that the ones badly cracked will have the moisture in them from the cement, and those that have not yet cracked but are simply porous will be longer in having the moisture cooked out of them. In every case I think we can say that the moisture comes from the wet cement which is in the insulator and has never been dried out, and once the cement has been thoroughly dried out it takes up moisture again very slowly.

There was one place where he compared the loss of insulators in service and insulators left out of service, and he gives the two figures, 8.9 per cent for those in service, and 8 per cent for those that were lost while out of service. It must be confessed we cannot draw certain conclusions from these figures, but so far as the figures go they show that those that were in service had about 10 per cent greater loss than those out of service. If that is true, I think it substantiates the opinion of a good many of us that operation does deteriorate an insulator to a certain extent. There is one point in regard to that which I want to take up. The service was not hard on the insulator due to potential, since the potential per disk is rather low. Mr. Bang in one place mentions the fact that the deterioration of insulators is attributable to electrical causes, such as switching, surges, arcing ground, high-frequency discharges, etc. I have myself championed the high-frequency theory, having first, however, shown from all the figures that have been given that the mechanical troubles are the predominant ones. Mr. Gaby, in Canada, and more recently, Mr. Julian Smith, have given some figures, where they have taken many thousands of these disks down and examined them and the evidence is entirely concordant. The porcelain and iron have a different coefficient of expansion, the expansion of the iron being twice as great, and that difference in expansion is sufficient to cause heavy mechanical strains, whether the insulators are in the stations or out on the line. Out on the line, of course, the strains will be probably greater, because the temperature changes are greater. If we set aside all these, the majority that are cracked or damaged mechanically, there is still left a certain percentage which is damaged electrically or are poor electrically.

If we ask ourselves this question: Why is it that 90 per cent of the insulators do not crack mechanically?—we will reach the first conclusion, that perhaps there is something in the ceramic side. Having gone through a great many electrical tests, I have concluded that the problem at the bottom is mainly ceramic. I have made a study on the ceramic side, in the matter of the compositions, and I can confirm some of the conclusions that Mr. Bang has drawn from his tests of soft spots or porous spots in the insulators. Porcelain is made up of three ingredients, clay, flint and feldspar—the feldspar acting as the flux. This material is ground up very fine, mixed in a big vat with water, and then subsequently the water is taken out by passing it through a filter press. In getting the water out these particles are segregated. A little more feldspar deposits in one spot, or there is a little more flint in one spot than in another. After this segregation has taken place, the manufacturer of porcelain attempts to get it all mixed up again by passing it as soft mud through a pug mill which also presses the air out of it. This mixes up the material again, more or less, but it never is thoroughly mixed. These spots in the porcelain are due to the fact that there is a lack of flux at that point. It is easy enough to duplicate these conditions by purposely putting in at different parts a little less than the proper amount of feldspar. Although in our experiments the firing was carried to one cone higher than the highest cone ordinarily used in porcelain work, the material remained quite porous and would absorb moisture.

In regard to Mr. Nicholson's short-circuit suppressor—I have worked along that same line, but have worked with slightly different methods of closing the circuit. The principle of the short-circuit suppressor is to throw the fuse across the circuit in parallel with the accidental arc that takes place out on the line. The fuse across the circuit reduces the voltage to zero, the arc goes out and subsequently the fuse blows. It is readily seen that the greatest importance must be placed on getting the arc out as soon as possible. If the arc could be put out during the first half-cycle in which it started there would be very little flame. If the arc is allowed to play for two or three cycles, the arc flame increases more and more in size, and it takes that much longer to extinguish it. So far, efforts have been along the line of throwing the fuse into the service in the same half-cycle in which the arc takes place. We have been able to do this by automatic means.

E. A. Lof: Mr. Bang's paper brings to my mind a large transmission system with a similar operating voltage of 70,000, which is at present being built in Sweden. A large amount of research work has been undertaken to determine the proper type and design of insulator, and a comparison of the two plants may be of interest.

The old line of the Pennsylvania Water and Power Company was equipped with five-unit insulators, this having been increased to seven-unit for the new line, the units of each string being identical. For the Swedish line, six-unit insulators were selected, but the units in each string are not identical, but graded.

It is well known that the potential is not evenly distributed along an insulator string of similar unit, but that the unit nearest the conductor is exposed to nearly three times the voltage across the unit nearest the crossarm or ground. For practical and economical reasons it was, however, not found advisable to make all the units of the insulator string of different capacity, and only three different kinds of units were used.

The potential distribution of both an ungraded and graded insulator string is given in the following table, the units being counted from the top.

	Potential in Per Cent of Total Voltage	
Unit	Ungraded	Graded
1	11%	15%
2	11	15
3	13	16
4	15	15
5	20	19
6	30	20

The outside diameters of all the units were maintained the same for practical reasons, and the different capacities were obtained by varying the thickness of the material. This is 18, 21 and 25 mm. respectively, corresponding to capacities of 49, 38 and 28 microfarads.

By providing a metal shield under the bottom unit it was possible to equalize still further the potential gradient along the string.

Before cementing the caps and bolts, both the inside and outside surfaces of the insulator head were coated with a layer of graphite and waterglass, and these conducting layers were connected to the cap and bolt respectively by means of tinfoil-covered asbestos washers as shown in Fig. 4. In this manner the cement is short-circuited and the charging current prevented from going through the same, and the danger of any electrolytic action caused by ionization of air pockets in the cement is thus eliminated.

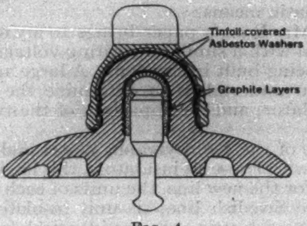


FIG. 4

E. E. F. Creighton: There is one point that is rather important from an engineering, and also from a practical standpoint. What is the solution of this problem and when are we to reach it? The present disk insulator has been put out in great numbers. It has taken more than a year for these troubles to show up. When we get a solution of this problem it will be at least a year before we know it. So far there has been about 10 per cent loss on this one line, and we do not want that to go any further. I recall a number of years ago that Messrs. Hewlett and Buck presented a paper on insulators not cemented in this way and in which there could be no strains from unequal expansion of the parts and the porcelain. Although that insulator has great difficulties in the way of manufacture, it may yet be called on as a solution of this particular problem.

L. C. Nicholson: I am glad to relate some experiences with suspension insulators in connection with temperature effects. A line containing 40,000 units which has been in service twelve months, was recently gone over with a megger and all the insulator units tested; and we found, as nearly everybody else finds, about 2.5 per cent of the units showed zero resistance. This represents the deterioration in the first twelve months. The line is new and therefore we have no further data. Looking into those which proved to be defective, we found that probably 90 per cent of the failures were due to circumferential cracks in the porcelain at the base of the cap in a plane perpendicular to the pin, which indicates that the break is on account of pressure of the cap on the porcelain, presumably on account of temperature effects.

Since such a large percentage of failures were characterized in that way, it appeared to us that some steps should be taken to relieve this pressure. Some fruit-jar rubber bands or equivalent were put on some of the new ones around the base of the cap, and we also made some experiments in painting certain sections of the pin to prevent compression caused by unequal expansion in metal and porcelain. We do not know that either of these changes will do any good, but in view of this serious defect in suspension type insulators we are ready to try almost anything suggested.

Looking at the table of Mr. Bang's paper, the one referring to the partial interruptions and total interruptions, in 1911 the total interruptions were twenty-three, in 1912 these were decreased to three. I think the paper states that the various devices which were put in to correct the flash-over troubles were installed in 1913 and 1914. However, they were in partly during 1912, which accounts for the reduction from all total interruptions in 1911 to nearly all being partial interruptions in 1912.

J. B. Leeper: In Mr. Downing's paper, he says: "Subsequent experience has shown that the average tower is of too complicated structure to accurately calculate the stresses in the different members, and it is now generally conceded that the best and only safe way to get reliable information as to the stability of a tower is to subject it to actual test." That is largely so, due to the shape of the tower. The statement is not correct that we cannot make a frame structure in which the stresses can be figured. If the towers are properly shaped, the stresses can be figured from the assumed loads, but if we do not properly shape them, then the statement is correct.

Ralph Bennett (by letter): The design of the towers for a transmission line must be based on the ordinary principles of framed structures. All stresses received above the foundation line pass down to the foundation through some form of a truss.

The uniform loading of the members in a truss depends on the relative stiffness (rigidity) of the members and on the type of connection used.

If a tower is framed of a double set of members working in multiple, part of them in tension and part in compression, the connections must be entirely without play or the two sets of members will load unequally. Any slippage or movement at the panel points will permit some members to relieve themselves and overload others.

Most such towers are erected with single bolted field joints at every intersection. To develop full calculated tower strength all of these joints must be drawn up so tight that they hold by side friction. If improperly assembled or strained in erection or if erected on an uneven foundation the added stresses so produced must remain in the structure.

The calculation of towers and the shop tests on assembled towers are based on the assumption that the tower stands on and is rigidly fastened to an unyielding base. This is a purely theoretical assumption and in order to render it tenable many lines of towers have been erected on massive blocks of concrete where all the legitimate stresses could have been handled with a better factor of safety by simpler towers standing on properly designed anchor plate footings.

If the tower structure itself is a rigid unit down to the top of the foundation members, there will be transmitted into them but a simple uplift and down thrust with a relatively slight horizontal component.

But if the open scissors type of bottom leg is used there is added the strain which the bottom tie should carry. This may become many thousands of foot-pounds and as the soft earth yields it becomes cumulative.

Figs. 5 and 6 show a typical failure of this class of tower when erected on earth footplates. Eleven miles of this line fell in a single storm. The original cost of the towers would have been less if a stable type of structure had been selected. The line was put on concrete bases, generally reinforced at numerous points and has given but little further trouble.

With a closed truss tower transmitting all stresses through adjustable tension diagonals the tower structure is complete in itself. It can be adjusted after erection to eliminate any internal stresses due to erection, unequal footings, etc.

The tower can be "kicked" in place, adjusted and left as a symmetrical structure which can be readjusted at any time for change of conditions. Figs. 7 and 8.

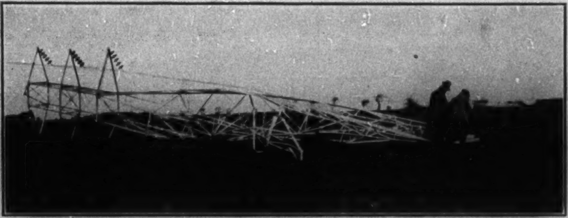
In this class of structure the members are few and relatively heavy. The proportion of exposed surface to area is low. So the weight of protective coating to the weight of members will be low. As the members will be stiff and immovable after erection the damage to the coating due to handling and load movements will be slight and the life of the tower long.

The simple members and plain fabrication as well as the small cost of galvanizing all tend to make the price per pound very low.

That the tower can safely be erected on earth plates is an additional reason for the low cost of transmission line on tension rod towers.

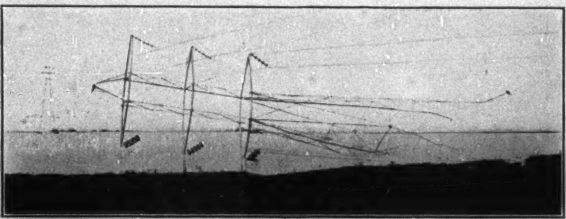
This class of structure is increased or decreased in height by the number of panels erected. This is readily adjusted and results in a saving in moderately rough country of 15 per cent in the average height of tower required.

The general design of earth plate footing is very simple with a properly framed tower.



[BENNETT]

FIG. 5—FAILURE OF SCISSORS TYPE OF TOWER—11 MILES OF THIS LINE FELL IN ONE STORM—COMPRESSION FAILURE

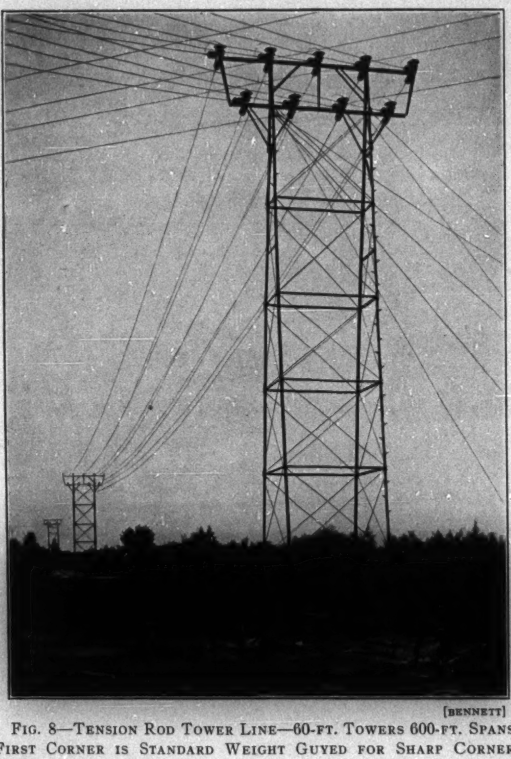


[BENNETT]

FIG. 6—FAILURE OF SCISSORS TYPE TOWER—INITIAL FAILURE DUE TO TOO SMALL FOOTING PLATES AND IMPROPER LEG DESIGN

[BENNETT]

FIG. 7—TYPICAL MOUNTAIN TRANSMISSION LINE—20 PERCENT LESS AVERAGE HEIGHT OBTAINED BY GRADED HEIGHT OF TOWERS



[BENNETT]

FIG. 8—TENSION ROD TOWER LINE—60-FT. TOWERS 600-FT. SPANS—FIRST CORNER IS STANDARD WEIGHT GUYED FOR SHARP CORNER—EARTH FOOTINGS

For the compression loading it is necessary that the plate be of sufficient size and properly bedded. The uplift condition always calls for a larger plate and the bedding is a matter of proper care.

For the uplift the plate if narrow will, in a large hole, permit the back fill to flow around it without developing any considerable fraction of the uplift calculated on the basis of an inverted cone.

Even if installed as a large plate in a narrow but wide-topped hole the weight of the earth actually lifted by the plate during the first few years will not much exceed the width of the hole.

But if the plate can be installed in a narrow hole with a chocked top the uplift will come partly against the undisturbed earth and part of the calculated weight will be available.

In all earth footing the resistance to uplift may be said to be successfully developed if the hole is very deep for its width and the plate is in addition caught under the undisturbed soil.

The Kern River line of the S. Cal. Edison Co., designed and built by the writer over 10 years ago, embodied tension rod towers on footings of this type. No tower has yet failed from either tower or internal footing difficulties. Some towers have been undermined by floods and have fallen.

There are now available many forms of expansible footing plates developed as guy anchors but capable of application as tower footings. These will take a deep secure hold on the undisturbed earth and should furnish an additional means of security.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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FIELDS OF MOTOR APPLICATION

BY DAVID B. RUSHMORE

ABSTRACT OF PAPER

This paper is to serve as an introduction to a discussion on the subject of Fields of Motor Application. An industry is defined from an economic standpoint and a list of the principal industries is given. The special points of interest in an industry are given and these are expanded to cover most of the items which would be of interest in investigating an industry from the standpoint of the application of electric motors.

THE NATURAL development of a country takes place through the successive activities of exploration, hunting and fishing, lumbering, mining, agriculture and manufacturing.

Manufacturing is defined by the Century dictionary as "The operation of making goods or wares of any kind; the production of articles for use from raw or prepared materials by giving to these materials new forms, qualities, properties or combinations, whether by hand labor or machinery."

Broadly speaking, the world's activities consist of the production, transportation, distribution and consumption of the necessities of life which, in general, consist of food, clothing and shelter. This may be likened to the generation, transmission, distribution and utilization of electric energy.

Raw materials, in general, consist of matter and stored energy in various forms of fuel. Most industries can be classified under the three general headings of food, clothing and construction. A somewhat more general classification is as follows:

Stone, clay and glass products.
Metals, machinery and conveyances.
Wood manufacturings.
Furs, leather and rubber goods.
Chemicals, oils and paints.
Printing, and paper goods.
Textiles.
Clothing, millinery, laundry.

Food, liquors and tobacco.
Water, light and power.

The various industries of the United States and some statistical information pertaining thereto are included in the following tables taken from the latest published Census Reports:

MANUFACTURES IN THE UNITED STATES.

(From Census Bureau's Summary for 1909, issued April, 1912.)

Statement of the general results of the Thirteenth United States Census of Manufactures.

SUMMARY FOR THE UNITED STATES FOR 1909.*

	CENSUS.		Per Cent of Increase, 1904to1909
	1909	1904	
Number of establishments	268,491	216,180	24.2
Persons engaged in manufactures	7,678,578	6,213,612	23.6
Proprietors and firm members	273,265	225,673	21.1
Salaried employes	790,267	519,556	52.1
Wage-earners (average number)	6,615,046	5,468,383	21.0
Primary horse power	18,680,776	13,487,707	38.5
Capital	18,428,270,000	12,675,581,000	45.4
Expenses	18,453.080,000	13,138,260,000	40.5
Services	4,365,613,000	$3,184,884,000	37.1
Salaries	$938,575,000	$ 574,439,000	63.4
Wages	$3,427,038,000	$2,610,445,000	31.3
Materials	12,141,791,000	$8,500,208,000	42.8
Miscellaneous	$1,945,676,000	$1,453,168,000	33.9
Value of products	20,672,052,000	14,793,903,000	39.7
Value added by manufacture (value of products less cost of materials)	$8,530,261,000	$6,293,695,000	35.5

*Not including Alaska, Hawaii or Porto Rico.

Manufacturing industries are of interest from the standpoint of economics, finance and investment, labor, tariff, power consumption, etc.

POINTS OF INTEREST IN AN INDUSTRY

All industries are identified by the
Finished Product, which is made from
Raw Materials by a
Manufacturing Process with an
Equipment which is driven by
Power and supplied with
Labor in a
Factory involving
Costs and other features of interest; some of which are
Transportation, Market, Competition, Financial Aspect, History, etc.

MANUFACTURES BY INDUSTRIES.

Industries.	Average Number of Wage-Barners.	Value of Products	Value Added by Manufacture	Per Cent Increase in Ten Years	
				(*a*)	(*b*)
Slaughtering and packing	89,723	$1,370,568,000	$168,740,000	29.5	73.8
Foundries and machine shops	531,011	1,228,475,000	688,464,000	24.4	53.9
Lumber and timber	695,019	1,156,129,000	648,011,000	36.6	51.9
Iron and steel, steel works	240,076	985,723,000	328,222,000	31.0	65.1
Flour and grist mills	39,453	883,584,000	116,008,000	22.4	76.2
Printing and publishing	258,434	737,876,000	536,101,000	32.4	86.7
Cotton goods	378,880	628,392,000	257,383,000	25.1	85.3
Clothing, men's	239,696	568,077,000	270,562,000	52.1	75.4
Boots and shoes	198,297	512,798,000	180,060,000	31.1	76.8
Woolen, worsted and felt goods.	168,722	435,979,000	153,101,000	29.1	75.2
Tobacco	166.810	416,695,000	239,509,000	25.9	58.0
Car shops	282,174	405,601,000	206,188,000	62.5	86.0
Bread and bakeries	100,216	396,865,000	158.831,000	66.5	126.3
Iron and steel, blast furnaces	38,429	391,429,000	70.791,000	†2.1	89.3
Clothing, women's	153,743	384,752,000	175,964,000	83.6	141.5
Copper, smelting and refining	15,628	378,806,000	45,274,000	38.0	129.4
Liquors, malt	54,579	374.730,000	278,134,000	38.3	58.2
Leather	62,202	327,874,000	79,595,000	19.4	60.7
Sugar and molasses not inc.beet	13,526	279,249,000	31,666,000	†41.3	16.5
Butter, cheese and milk	18,431	274,558,000	39,012,000	44.0	109.9
Paper and wood pulp	89,492	267,657,000	102,215,000	53.0	110.2
Automobiles	75.721	249,202,000	117,556,000	3278.9	5148.6
Furniture	128,452	239,887,000	131,112,000	41.8	83.6
Petroleum refining	13,929	236,998,000	37,725,000	14.2	91.2
Electrical machinery	87,256	221,309,000	112,743,000	107.7	139.4
Liquors, distilled	6,430	204,699,000	168,722,000	72.8	111.5
Hosiery and knit goods	129,275	200,144,000	89,903,000	54.5	108.8
Copper, tin and sheet iron	73,615	199,824,000	87,242,000	92.1	155.0
Silk and silk goods	99,037	196,912,000	89,145,000	51.4	83.6
Lead, smelting and refining	7,424	167,406,000	15,443,000	†10.8	4.6
Gas, illuminating and heating	37,215	166,814,000	114,386,000	65.7	120.3
Carriages and wagons	69,928	159,893,000	77,942,000	†5.3	15.6
Canning and preserving	59,968	157,101,000	55,278,000	5.2	58.2
Brass and bronze	40,618	149,989,000	50,761,000	49.5	69.2
Oil, cottonseed	17,071	147,868,000	28,035,000	55.1	151.8
Agricultural implements	50,551	146,329,000	86,022,000	8.5	44.6
Patent medicines	22,895	141,942,000	91,566,000	20.3	59.9
Confectionery	44,638	134,796,000	53,645,000	66.2	122.3
Paint and varnish	14,240	124,889,000	45,873,000	46.8	79.5
Cars, steam railroad	43,086	123,730,000	44,977,000	28.8	36.7
Chemicals	23,714	117,689,000	53,567,000	24.7	87.6
Marble and stone work	65,603	113,093,000	75,696,000	57.4	77.6
Leather goods	34,907	104,719,000	44,692,000	19.2	73.3
All other industries	1,634,927	4,561,002,000	2,084,399,000	46.9	100.7
All industries, total	6,615,046	$20,672,052,000	$8,530,261,000	40.4	81.2

*In the year 1909. (*a*) Increase in average number of wage-earners, 1899-1909. (*b*) Increase in value of products, 1899-1909. †Decrease.

In the above table the industries are arranged in the order of their gross value of product, Some of the industries which hold a very high rank in gross value of products rank comparatively low in the average number of wage-earners employed and in the value added by manufacture. Where this is the case it indicates that the cost of materials represents a large proportion of the total value of products, and that therefore the value added by manufacture, of which wages constitute usually the largest item, is not commensurate with the total value of products.

In investigating or describing the application of electricity to various industries, the following subjects form a tentative and necessarily incomplete list of the points of interest:

FINISHED PRODUCT

Description, Complete, Detailed, Condensed Composition, Chemistry.

Uses of Product.

Historical Sketch.

Seasonal Production or Consumption, Operation of Factory. To be sold for consumption or to pass through further manufacturing processes.

Ability to undergo Storage.

Limitation regarding time of shipment and consumption as related to manufacturing, dairy products, fruit, etc.

Ability to withstand transportation.

Conditions of boxing and other preparations for shipment.

Factors or conditions which injure product.

Quality of product, Affected by what factors?

Size factor, per unit or per pound.

Weight factor, Weight of shipping unit, also per cu. ft., etc., also per unit.

Shipping by mail, express, freight; rates.

Preparation for market.

Specifications to be met.

Tests.

Grades and characteristics.

Reputation, Brands, Trade Marks, etc.

Substitutes.

Product is sometimes Labor or Service.

Stock.

Cost Analysis, also Diagram of general cost plan.

Price fluctuation over term of years.

Production by countries and localities over term of years.

Consumption by countries, localities, trades, etc.

By-products.

Waste, Refuse, Scrap, Unsalable Residue.

Exports and Imports.

RAW MATERIAL

Source, Geographical, Manufactured.

Classification, Grades, etc.

Export and Import.
Production, Country, Seasonal.
Control or Open Market.
Natural or Manufactured Products.
Limitation to Supply.
Substitutes.
Percentage Loss Necessary, Raw Material to Finished Product.
Specifications and Tests, Inspection, Varieties, Grades, Impurities.
Purchasing.
Storage.
Stock to be kept on hand.
Per cent of Cost of Product.
Adulterants Used.
Indications of Purity.
Undesirable Ingredients.
Ownership of Supply.
Preliminary Treatment.
Danger to which it is exposed, Depreciation with Age, Moisture, Heat, Cold, Vibration, etc.
Seasonal Production.
Price Fluctuations over Term of Years.
Transportation, Costs and Ability to Withstand.

MANUFACTURING PROCESS

Characteristics of Raw Material as received.
Preliminary Treatment Necessary.
Description of General and Detailed Steps in Process by which the Raw Material is Converted into Finished Product.
Particular Requirements of Process as regards Time, Temperature, Pressure, Power, Speeds.
Critical Points in Process, Method of Determination, Precautions.
Diagram of Flow of Material through Process.
Possible points for improvements.
Alternative processes possible with relative advantages and Disadvantages of each.
Mixtures of ingredients to be used with specifications and the results of variation of quantity and quality.
Result of stoppage of any part or all of plant.
Use of steam for manufacturing purposes.
Use of Water, Gas, Oil and Coal for manufacturing purposes other than power.

EQUIPMENT AND POWER

List of steps in Process and Description of Machine used for each step.

List of Manufacturers of each kind of Machine.

Load Curves or Duty Cycle of each Machine.

Conditions, of Starting, Accelerating, Running, Braking, Reversing, etc.

All Factors involved in the Motor Application such as Atmospheric Conditions, of Dust, Injurious or Inflammable Gases; exposure to outside heat, vibration, noise, safety precautions, illuminations, accessibility of repairs, use of flywheels, protection for belts, etc.; method of mounting, method of drive, ventilation, shaft extensions, lubrications, clutches, oil drainage, type of frame, methods of adjustment and alignment, etc, etc.

Photographs and Drawings of Machines showing mounting of Motor and Control wherever possible.

Points determining Type and Capacity of Motor.

Points determining Type and Capacity of Control.

Distributing System.

Generating System.

Methods of Measuring Power Consumption.

Important Points in Power Contract.

Cost of Manufactured or Purchased Power.

Load Curve of Plant as a whole.

FACTORY

1. Location of factories manufacturing product with reasons for such location and output of each.
2. Ground plan of factory showing generating plant or substation, Buildings, Location of machines, Path of flow of materials, etc.
3. Elevation of principal buildings where this will give desirable information.
4. Diagram of electric distributing circuits.
5. Storage facilities for raw material and product.
6. Methods of illumination.
7. Safety precautions.

LABOR

1. Location of factory.
2. Existence of special class of labor especially skilled in industry.
3. Curve of wages over term of years.

4. Relative labor efficiency.
5. Relative costs of operations by hand labor and electrically driven machinery.
6. General intelligence of labor and care of apparatus which may be expected.

Costs

1. Diagram and detailed description of methods of estimating cost of product and of factors involved.
2. Tabulation of cost factors in per cent of the whole, showing the relative importance of the items of power, labor and materials.
3. Indicate directions in which effort can be most advantageously employed toward saving in cost and improvement in quality of product.
4. Outline in detail economic value of electric drive.

As a factor of greater efficiency and saving in power cost.

As allowing the purchase of power and therefore the reduction of capital investment.

Increased production for a given equipment.

Improvement in the quality of product due to constant speed.

The possibility of centralizing the power supply.

Simplicity in power transmission and distribution.

Convenience in location of machinery with reference to production rather than to power transmission system.

Ease of making changes.

Reduction of friction losses.

Improved cleanliness and better light and safety due to absence of large number of belts.

Greater reliability in operation.

Possibility of selection of suitable motors.

Ease of control.

Possibility of remote and automatic control.

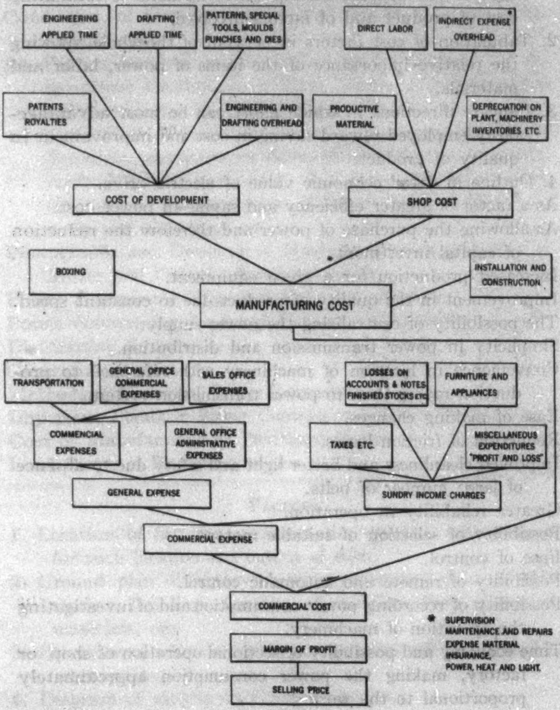
Possibility of recording power consumption and of investigating the operation of machinery.

Time economy and possibility of sectional operation of shop or factory, making the power consumption approximately proportional to the work.

The following diagram of costs is impersonal and does not represent the practise of any one particular company. The proper method of estimating costs is, however, so little understood by manufacturing concerns that but few include all of the items which really make up a part of the total expense involved in the production of a product.

In order to appreciate the economic part played by the electric motor in manufacturing industries it is necessary to have the detailed cost sheet. The valuation of the various factors of advantages of the electric motor application, other than those involved in the direct reduction of power cost, is a treatment so special as to necessitate its separate statement for each industry.

ITEMS IN THE COST OF A FINISHED PRODUCT


ENGINEERING APPLIED TIME
DRAFTING APPLIED TIME
PATTERNS, SPECIAL TOOLS, MOULDS PUNCHES AND DIES
DIRECT LABOR
INDIRECT EXPENSE OVERHEAD *
PATENTS ROYALTIES
ENGINEERING AND DRAFTING OVERHEAD
PRODUCTIVE MATERIAL
DEPRECIATION ON PLANT, MACHINERY INVENTORIES ETC.
COST OF DEVELOPMENT
SHOP COST
BOXING
INSTALLATION AND CONSTRUCTION
MANUFACTURING COST
TRANSPORTATION
GENERAL OFFICE COMMERCIAL EXPENSES
SALES OFFICE EXPENSES
LOSSES ON ACCOUNTS & NOTES FINISHED STOCKS ETC
FURNITURE AND APPLIANCES
COMMERCIAL EXPENSES
GENERAL OFFICE ADMINISTRATIVE EXPENSES
TAXES ETC.
MISCELLANEOUS EXPENDITURES "PROFIT AND LOSS"
GENERAL EXPENSE
SUNDRY INCOME CHARGES
COMMERCIAL EXPENSE
COMMERCIAL COST
MARGIN OF PROFIT
SELLING PRICE
* SUPERVISION
MAINTENANCE AND REPAIRS
EXPENSE MATERIAL
INSURANCE,
POWER, HEAT AND LIGHT.

The object of this paper is to give a brief outline of the points of interest in industry and to point out the factors involved in the application of electric motors to manufacturing purposes. It is intended to serve as an introduction to a discussion which will bring out the points of interest in the various industries in which the electric motor has been applied.

This paper is the fourth and last part of a treatment of Industrial Power Applications, the other parts of which have been Electric Motors, Electric Controllers, and the Factors Involved in Motor Application, which were presented respectively at the New York, Pittsburgh and Cleveland Meetings.

Presented at the 32d Annual Convention of the American Institute of Electrical Engineers, Deer Park, Md., June 29, 1915.

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ELECTRICITY IN GRAIN ELEVATORS

BY H. E. STAFFORD

ABSTRACT OF PAPER

The object of this paper is to show the storage capacity of grain at the terminals of Port Arthur and Fort William, the rated horse power capacity of prime movers, the amount of power used to turn out a given quantity of grain, and the power used by different machines in the process. In addition it gives the details of different plants as regards construction and operation and the method of receiving and shipping grain. It gives a comparison between steam and electrically-driven plants as regards convenience, maintenance, operation and cost. As regards the station end, it shows the lay-out of different stations, the cost of installation, the operation and in some instances, the cost of power. It will be shown in the paper that the cost of handling grain varies, and the reason is fully described. On account of the grain handling season being of short duration, it is the intention of certain companies to install turbo-generators to overcome the necessity of paying on a peak demand basis. By installing two or more units the operating expenses would be cut to a minimum. With the use of steam power this is impossible.

ELECTRIC power first came into the limelight in this industry in Fort William, in 1902, making this city one of the pioneers in this respect. Electricity was first introduced by the Canadian Pacific Railway, which built a power house operated by steam, for the purpose of electrifying its numerous elevators. This company was the only one using electric power until the advent of the Kaministiqua Power Co., in 1905. The latter company established a power house at the foot of Kakebeka Falls, 18 miles from Fort William, in June 1905, and the first two units of 7000 h.p. capacity were put into operation in December, 1906. A third unit of 7000 h.p. was added in October, 1911, while a fourth unit of 13,000 h.p. was added in August, 1914, making a total of 27,000 h.p. Fig. 1 shows the location of the power house and flumes.

At this point the power is generated at 4000 volts, and stepped up to 25 kv. It is transmitted at this voltage to substations at Port Arthur and Fort William, where it is stepped down to 2200 volts. The loss in transmission is approximately 3000 volts.

The substation at Fort William has, at present, three banks of three transformers with a capacity of 5500 kv-a. for each bank. The station at Port Arthur has six transformers of 750 kv-a. each. The connections from power house to station are star-star, star-delta, with grounded neutral. The Corporation of Port Arthur has in addition, a hydroelectric plant at Current River with a total capacity of 2500 kv-a., at 2200 volts, which is used at the heaviest load period to keep down the peak.

Under the names of the different plants will be given a brief description of the various conditions under which they work, obtain power, etc. The first two described are the latest built, and will be given in detail.

WESTERN TERMINAL ELEVATOR

This elevator is a recent type, and is the second in Fort William to purchase power at 22 kv. The station was completed in August, 1914. The old plant which was built a few years ago is of concrete, with steel and tile cupola, while the tanks are tile. The new house, built in 1914, is of reinforced concrete throughout. The building is built on a foundation of piles driven sixty feet below cut-off. The piles are driven in blue clay, and are capable of standing a stress of between 16 and 20 tons per pile. The grain capacity of the elevator is 2,000,000 bushels. The power contracted for is 700 h.p. The plant is equipped with 56 motors of a total capacity of 1140½ h.p. The motors are used for various purposes, some of which are given below.

There are two car-haul motors (one for each track) of 40 h.p. capacity each, capable of hauling 25 cars each. There are six receiving pits and three receiving legs with 22-inch buckets. Each leg is operated by a 75-h.p. motor. The distributing belt conveyers are operated by a 20-h.p. motor each, and the shipping belt conveyers are operated by a 15-h.p. motor each. The loading legs require from 60-h.p. to 75-h.p. motors each.

There are also seven cleaners and three cleaning legs. The cleaner legs take from 15 h.p. to 25 h.p. each, while the cleaners are operated by a 10-h.p. motor each. This plant is equipped with four flax machines, of 10-h.p. capacity each, and two special flax machines of 7½ h.p. each.

Two fans for collecting dust are operated by a 10-h.p. and 15-h.p. motor respectively, and the building is piped with compressed air supplied by a 4½- by 6-in. compresser for cleaning motors.

The station equipment consists of three 250-kv-a. single-phase transformers. The connections are star-delta. The power factor is kept at 90 per cent by two 125-kv-a. condensers. In addition there is a 30-kw. single-phase transformer for lighting purposes. The load factor is about 25 per cent.

Fort William Elevator Co.

This plant was built in 1913 and is of reinforced concrete with brick paneling. The plant, which has a grain capacity of 1,500,000 bu., is operated by both steam and electric power. The boiler capacity (four boilers) is 500 h.p. The engine capacity is 800 h.p. These operate at a steam pressure of 120 lb.

The electric plant consists of a 300-h.p. marine engine direct-connected to a 225-kw., 600-volt, 60-cycle, three-phase alternator supplying current to three 100-h.p. motors operating three shipping legs, four 15-h.p. motors operating four shipping conveyer belts, and one 20-h.p. motor operating a reversible conveyer belt.

The plant uses 2000 tons of coal per annum at a cost of $4.00 per ton. Below is given the cost of operating the plant for one year.

Coal	$ 8,000.00
Oil	250.00
Waste	32.00
Packing	200.00
Wages	4,000.00
Total per annum	$12,482.00

This makes an average of $34.194 per day. Average load for 365 days = 300 h.p. Average cost per h.p. per annum = $41.606. As this plant also supplies steam for the drier, the actual cost is somewhat below this amount, the actual cost not being known.

The storage capacity of the plant is 48 tanks, each containing 27,000 bu., and 35 intermediate tanks, each containing 7000 bu. There are six receiving pits capable of handling 12 cars or 13,200 bu. per hour. Also nine wheat cleaners and two flax cleaners of 1000 bu. capacity per hour.

The shipping capacity is about 45,000 bu. per hour, and each conveyer belt of 15 h.p. capacity handles 20,000 bu. per hour. Two extra features of this plant are a separater, for separating various grains, and a drying plant. The capacity of the drier is 1000 bu. per hour.

CONSOLIDATED ELEVATOR

The total grain capacity of this plant is 1,750,000 bu. Power is delivered at 2200 volts on a contract basis of 700 h.p. The average load is 600 h.p. The total number of motors is 37, ranging from 2 h.p. to 75 h.p., delivering 1007 h.p.

The transformer station consists of 2200 to 600-volt transformers, a synchronous condenser, necessary switch gear, and motors. All other characteristics correspond to the plants previously described.

CANADIAN PACIFIC RAILWAY CO.

As before stated, the C. P. R. was the pioneer in the use of electric power for elevator purposes. This plant, which is the only one operated by this company in this city, has a total grain capacity of 8,000,000 bu. and is the second largest plant in the world. The shipping capacity is 80,000 bu. per hour.

The company discontinued the use of its own power plant and purchased power from the Kaministiqua Power Co. in 1907. Power is purchased at 2200 volts and stepped to 600 volts at its own transformer station. The transformer capacity is three single-phase, 588-kv-a., or a total of 1764 kv-a. The power factor is maintained at 90 per cent by a 750 kv-a. condenser. The total motor capacity is 2100 h.p., while the average load is 1400 h.p.

CANADIAN NORTHERN RAILWAY ELEVATOR

This plant is a double one; that is, there are two work houses with the storage tanks between. It has a storage capacity of 9,500,000 bu. and is the largest plant in the world. This plant was first started in 1900, and has been added to at various times, the last addition being made in 1913. Up to that time it was a steam plant throughout, but when the annex was built in 1913, a 200-kv-a. three-phase generator was installed to supply power for it alone.

The total engine capacity of the plant is 2000 h.p. supplied by a 1250-h.p. and a 750-h.p. unit. The coal consumption of

FIG. 1 [STAFFORD]

FIG. 2 [STAFFORD]

this plant is 7000 tons per annum, 950 tons of which are used in the driers. The average horse power (steam) is about 1700. The cost of producing power is 0.9 cent per kw-hr. figured on a basis of 3½ lb. of coal per h.p-hour. Statistics of this plant also show that the cost for one year was $22.56 per h.p. for steam power which is an exceedingly low rate.

The average amount of grain handled in one year is 40,000,000 bu.

In Jan. 1914, the elevator was remodeled, necessitating the installation of additional power. As the company was considering using electric power throughout in the near future, it was deemed advisable to erect a substation to accommodate the extra power needed, which could be enlarged as more power was required.

The transformer station is a separate building of brick and tile construction, and was built in 1913. The equipment, which was installed and partly designed by the writer, was put in operation in April 1914. Power is purchased from the City of Port Arthur, at 22 kv., and stepped to 600 volts by three 150-kv-a. transformers connected to a six-panel board. The oil switches and busbars are mounted directly on the board, which consists of one main panel, one condenser panel, and four feeders. On the main panel is an ammeter giving the readings from the high-tension side of the transformers, a graphic wattmeter giving the total kilowatts of load, a graphic power factor meter and a maximum demand and integrating wattmeter combined. The voltmeter giving the low-tension readings is mounted on a swing bracket at the end of the board. The four feeders are duplicates and have only an ammeter each, with the necessary switchgear. A detail drawing of connections is shown in Fig. 3. This diagram corresponds to nearly all the low-tension connections in all the elevators. Fig. 2 shows a view of this board and part of the lightning arrester equipment.

A detailed drawing of the synchronous condenser panel is shown in Fig. 4. This consists of three a-c. ammeters, one a-c. voltmeter, one d-c. ammeter, one d-c. voltmeter, and oil switch, two rheostats, synchronizing lamps, switches, plugs and starting controller. The condenser itself is the 200-kv-a. generator mentioned before, and was installed in the station for power factor correction. The condenser is started somewhat differently from the others used in elevator practise (all others are self-starting) as this machine is started and brought up to speed (900 rev. per min.) by its exciter, which is supplied at 110 volts d-c. by a large generator supplying lights to the elevator. When the machine has reached synchronous speed it is thrown on the line in the usual way and the double-pole, double-throw switch shown in Fig. 4 is thrown to the running position, when the exciter takes care of the condenser, through the generator field rheostat, by which the power factor can be regulated at will. It takes one minute to get the condenser on the line.

The emergency switch mentioned in Fig. 4 is used in case the exciter needs repairs. In this case the fields can still be excited from the light generator while such repairs are being made, the condenser of course having to be kept running, as there would be no way of starting it. The short-circuiting switch is for cutting out the controller when the motor is running as an exciter.

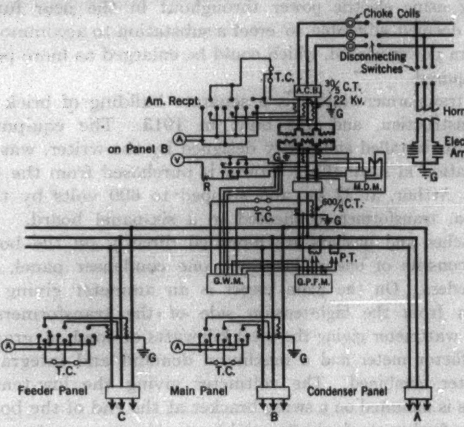
Choke Coils
Disconnecting Switches
T.C.
A.C.B.
30/5 C.T.
22 Kv.
G
Am. Recpt.
Horn Gaps
Electrolytic Arrester
G
A
on Panel B
V
G
R
M.D.M.
600/5 C.T.
T.C.
G
P.T.
G.W.M.
G.P.F.M.
A
G
T.C.
A
G
T.C.
Feeder Panel
Main Panel
Condenser Panel
C
B
A

FIG. 3

C.T., current transformer; *P.T.*, potential transformer; *T.C.*, trip coils; *A.C.B.*, automatic circuit breaker; *M.D.M.*, maximum demand meter; *G.W.M.*, graphic wattmeter; *G.P.F.M.*, graphic power factor meter.

The total capacity of the switchgear is about 2000 h.p., while the capacity of the transformers is only 450 kv-a. These of course can be added to at any time. The transformers are delta-delta connected. The station is protected by three electrolytic lightning arresters. The total motor capacity at present is 765 h.p., while the average load is 385 h.p.

GRAND TRUNK PACIFIC ELEVATOR

This elevator has a grain capacity of 5,750,000 bu. The motor capacity is 1800 h.p. It was the first in this district to purchase power at 22 kv., having contracted for it in 1909. The substation is large and roomy with a maximum of safety. The building is three stories high. The top floor contains the choke coils, lightning arresters and high-tension switchgear. The arresters are the electrolytic type. The second floor contains the light and power transformers. There are three single-phase 22-kv. to 600-volt transformers with a total capacity of 2025 kv-a., and three lighting transformers of 60 kv-a. each. The ground floor is taken up with the condenser and switchboard. The condenser is self-starting and has a capacity of 750 kv-a.* It draws about 800 amperes at starting, and takes about 1½ minutes to get it on the line. The switchgear and

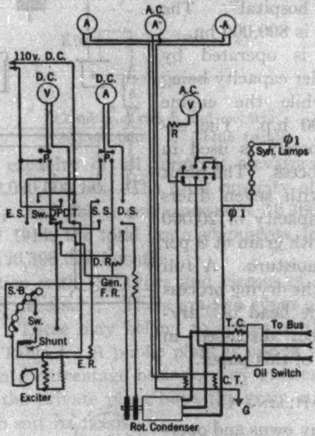

FIG. 4—SYNCHRONOUS CONDENSER PANEL

P., voltmeter-ammeter plug; *S.B.*, starting box; *Gen. F.R.*, generator field rheostat; *D.R.*, discharge resistance; *S.S.*, short circuiting switch; *E.S.*, emergency switch; *D.P. D.T. Sw.*, double pole, double throw switch; *D.S.*, discharge switch; *E.R.*, exciter rheostat; *C.T.*, current transformer; *T.C.*, trip coils.

buses are mounted directly on the board. An extra feature of this station is a fire pump of 500 gallons per min. capacity, driven by a 50-h.p. motor. Fig. 5 shows the elevation of a substation of this type.

THE HORN ELEVATOR

This plant, better known as "King's elevator" was built in 1883 and is the oldest elevator in this part of the country. This elevator, is an exclusive cleaning and drying plant and is called a "hospital". The grain capacity is 800,000 bu.

The plant is operated by steam, the boiler capacity being 1200 h. p. while the engine capacity is 600 h.p. The excess boiler capacity is used in the drying process. The plant is equipped with seven driers with a total capacity of 20,000 bu. per day, with grain at 8 per cent excess moisture. A full description of the drying process comes under the head of "drying," a subject discussed in the latter part of this paper.

OGILVIE MILLING CO.

This company owns and operates an elevator in connection with its flour mill. The grain capacity of the elevator is 1,250,000 bu., while the capacity of the mill is 3000 bbl. per day.

The rated capacity of motors is 2000 h.p. and the power is purchased on a 1300-h.p. demand basis. Power is delivered to the plant at 2,200 volts and stepped to 600 volts. The milling machinery is connected to a lineshaft driven by an 800-h. p. motor, while the mill cleaning equipment is lineshaft connected to a 250-h.p. motor.

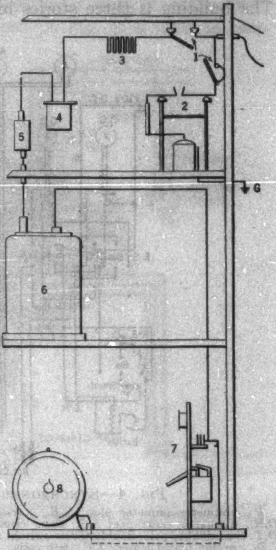

FIG. 5

1—discharge switches; 2—electrolytic lightning arresters; 3—choke coils; 4—high-tension oil switch; 5—current transformer; 6—transformer; 7—switchboard; 8—condenser.

The plants described above cover the field very well, and for the sake of convenience, the balance of the plants at these terminals, as well as the preceding ones, are given in Table I. This table covers all the data available. It is impossible to obtain all the facts and figures, as most of the companies are very reticent in this respect.

SUMMARY

The power applied to grain elevators, steam and electric, may be summarized as follows:

total h.p.	Electric power (max. demand)	average h.p.
14,412½		8680
	Electric power (flat rate)	
495		475
	Steam power	
4,710		3105
	Combined steam and electric	
800 steam	365 electric (1165 total)	300

The total capacity of all terminal elevators as shown in Table I is 42,090,000 bu. The total capacity of prime movers is 19,982½ h.p. and the average power is 12,360 h.p. During the season of 1914, the total grain shipments from these terminals was 126,398,622 bushels.

In connection with the types and classes of plants, a little explanation is necessary. There are two types of plants, public and private. These may belong to either of the two classes, as shown in Table I. A public plant is one in which the grain is handled on a percentage basis for any grower or grain company, while the private plant buys the grain outright and disposes of it to suit its needs.

The cost of handling grain is rather hard to figure. A plant may not handle the same amount of grain two years in succession. It may also be stated that, while the characteristics of these elevators as to major details are identical, the conditions under which they operate are at a variance.

It has been shown in Table I, that a certain plant handles 20,000,000 bu. of grain on 1500 tons of coal at $4.00 per ton. Including the operating costs, the cost per bushel over a number of years was shown to be 0.057 cent per bu.

Another plant handled for one year, 30,000,000 bu. of grain on 675 kw. at a maximum demand charge of $10,492.44 on a basis shown at the conclusion of this paper. This brought the cost per bushel down to 0.035 cent per bu.

TABLE I

SQUIRREL-CAGE MOTORS USED IN ALL PLANTS

No.	Name	No. plants	Grain capacity bushels	Motor cap. h. p.	Enginecap. h. p.	Boiler cap. h. p.	Average h.p. elec.	Average h.p. steam	Transformer cap. kv-a.	Condenser cap. kv-a.	Load factor[1]	Power factor
1	Western Terminal	1	2,000,000	1,140½			700		750	250	25%	90%
2	Fort William Elev.	1	1,500,000	365	800	500	100	200				
3	Consolidated Elev.	1	1,750,000	1,007			600		750	200		90
4	Can. Pac. Ry.[6]	1	8,000,000	2,000			1400		1,764	588		90
5	Can. Nor. Ry.[3]	2	9,500,000	765	2000	2000	385	1700	450	200		92
6	Grand Trunk Pac. Ry.	1	5,750,000	1,800			1500		2,025	750		90
7	Horn Elevator	1	800,000		600	1200		600				
8	Ogilvie Milling Co.	1	1,250,000[2]	2,000			1300		1,800			90
9	Grain Growers Co.	3	2,500,000	1,450			900		600	600	45%	90
10	Eastern Terminal	2	1,250,000	1,300			450		525	450	12.15%	90
11	Empire Elevator[5, 6]	1	1,750,000		650	550		300				
12	Thunder Bay Elev.[5, 6]	1	1,500,000		650	550		300				
13	Can. Gov. Elev.	1	3,125,000	2,150			1000		1,300	750		92
14	Smith Davidson Co.	1	750,000	500			125		450	150		92
15	N. M. Paterson Co.[4]	2	175,000	250			250		270			90
16	Parrish & Heimbecker[4]	1	100,000	145			125		150		45%	90
17	Bole Grain Co.[4]	1	20,000	20			20		20			90
18	Muirhead & Co.[4]	1	30,000	30			30		30			90
19	Guy Elev. Co[4]	1	35,000	50	10	15	50	5	45			90
20	Dwyer Elev. Co.	1	100,000	110			90		120			90
21	Muirhead & Black	1	165,000	100			130		120			90
22	National Elev. Co.	1	40,000	90			100		90			92
	Total	27	42,090,000	15,272½	4710	4815	9255	3105	11,259	3938		

---

1. Load factor not available in most cases as no accurate records are kept. 2. Capacity 3000 bbl. per day. 3. Maximum demand charge $27.618. 4. Flat rate charge $27.00 h. p. 5. Cost per bus. 0.057 cent. 6. Cost per ton of coal $4.00.

TABLE I—Continued.

No.	Name	H. P. voltage	L. T. voltage	Contract	Coal consumption per annum tons	Average grain handled per annum bushels	Remarks
1	Western Terminal	22,000	600	max. demand			
2	Fort William Elev.[6]				2000		
3	Consolidated Elev.	2,200	600	max demand			
4	Can. Pac. Ry.[6]	2,200	600	"			
5	Can. Nor. Ry.[3]	22,000	600	"	7000	40,000,000	
6	Grand Trunk Pac. Ry	22,000	600	"			
7	Horn Elevator						
8	Ogilvie Milling Co.	2,200	600	"			
9	Grain Growers Co.	2,200	600	"			3 plants supplied by one station 2 of the plants owned by the Can. Pac. Ry.
10	Eastern Terminal	2,200	600	"			2 plants supplied by one station both plants owned by the Can. Pac. Ry.
11	Empire Elevator[5, 6]				1500	20,000,000	actual cost over a number of years as shown later.
12	Thunder Bay Elev.[5, 6]				1500	20,000,000	actual cost over a number of years as shown later.
13	Can. Gov. Elev.	22,000	600	"			
14	Smith Davidson Co.	22,000	600	"			flour mill is to be erected in connection with this plant
15	N. M. Paterson Co.[4]	2,200	600	flat rate			each plant has its own bank of transformers, and one plant has an unloading *spout cap.* 6000 *bus. per hr.* at 50 h.p.
16	Parrish & Heimbecker	2,200	600	"			equipped with oat clipper, cooler, and scalper (see Fig. 7) Cap. of cooler 3600 bus. per hr.
17	Bole Grain Co.[4]	2,200	600	"			equipped with a sacker.
18	Muirhead & Co.[4]	2,200	600	"			
19	Guy Elev. Co[4]	2,200	600	"			equipped with a hot air drier, engine driven.
20	Dwyer Elev. Co.	2,200	600	max. demand			
21	Muirhead & Black	2,200	600	"			max. demand exceeds rated motor capacity.
22	National Elev. Co.	2,200	440	"			max. demand exceeds rated motor capacity. equipped with a grinder and sacker.

Another plant handled 500,000 bu. on 100 h.p. flat rate at $25 per h.p. or 0.05 cent per bu.

From Table I, item 5, it will be seen that this plant handled 40,000,000 bu. on 7000 tons of coal, which, with the operating expenses, brought the price to 0.042 cent per bu.

As stated before, this information, while authentic for the period mentioned, can hardly be called an average.

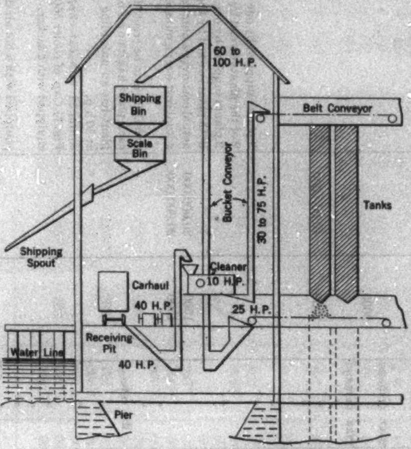
60 to 100 H.P.
Shipping Bin
Scale Bin
Belt Conveyor
Bucket Conveyor
30 to 75 H.P.
Tanks
Shipping Spout
Cleaner
10 H.P.
Carhaul
40 H.P.
25 H.P.
Receiving Pit
40 H.P.
Water Line
Pier

FIG. 6—DIAGRAM OF GRAIN ELEVATOR

HANDLING THE GRAIN IN ELEVATORS

The handling of the grain may be grouped under a number of headings such as:

1. Receiving; car haul, unloading.
2. Cleaning.
3. Conveying; storage tanks.
4. Conveying; hopper conveyer.
5. Weighing; shipping.
6. Drying.

Car Haul. The cars are shunted into the elevator by a yard engine, after which they are moved by a cable drum over the receiving pits. The size of the motors for the car haul depends on the capacity of the elevator and the average number of cars handled at one unloading. For a train of 25 cars a 40-h.p. motor is used.

The motor starts under no load and the load is gradually thrown on by a friction clutch attached to a cable drum. The strain is sometimes very great as for a train of 25 cars a 40-h.p. motor would exert itself 40 to 60 per cent above rated capacity. As this is only for a few seconds, the load as a whole is of little importance.

Unloading. The grain is shoveled from the cars by reverse cable shovels; generally two to a car, each operated by one man. Of course the greater part of the grain leaves the car by gravity as soon as the grain doors are removed, and the shovels are used for the remote corners and floor. It usually takes 30 min. to unload a car containing 1100 bu., 66,000 lb. Each receiving pit has a set of two shovels. The power required to operate two shovels is approximately 7.5 h.p. The load is intermittent and very seldom exceeds the normal capacity of the motor.

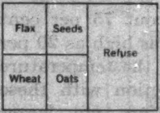

FIG. 7—SCALPER

This consists of five sieves, with a spout leading from each compartment to conveyers.

Cleaning. While the grain does not necessarily go through the cleaning process immediately after it is removed from the cars, this subject will be treated first. From the receiving pits, the grain is carried by bucket conveyers either to the cleaner or storage tanks, as the case may be. The cleaners are located on the first " deck " of the elevator. At the cleaner the grain is separated from the chaff, dirt, etc. The screenings (false grain and others) are transferred to a bin where they are afterward sold for feed. The chaff is drawn by suction into a blower and carried to the boilers direct. The foul seed is taken to a bin where it is afterward disposed of. The power required for the blower is from 15 h.p. for a 2,000,000-bu. plant, to 75 h.p. for a 9,000,000-bu. plant. The load is constant and never exceeds the full load rating. The motors for the cleaners range up to 10 h.p. and are never overloaded. The load is practically constant.

Conveying and Storage Tanks. The good grain is taken by a bucket conveyer from the cleaners to the tops of the tanks, where it is dumped on a belt conveyer, to be distributed to the various tanks. The tanks are constructed, as before stated, of steel, tile or concrete. A belt conveyer runs between two sets of tanks and the grain is shunted into the proper tank by means of a " dumper." This dumper consists of a set of rolls, between which the belt passes, on the same principle as a belt tightener. By closing the dumper the grain is diverted to a chute and then into the tank. The dumper is mounted on rails and is generally moved by hand.

The bucket conveyers require from 50 to 75 h.p. motor capacity, according to the height of the conveyer and the size of the buckets. These motors start under light load, but as soon as the grain starts the motor is loaded to its normal capacity. The belt conveyers probably have the heaviest conditions to work under, having to start under great stress, sometimes double their rated motor capacity, and in many instances the autostarters are of no use whatever, the handle having to be thrown to the running position to start. It is not an uncommon occurrence for a 15-h.p. motor to blow a 100-ampere fuse, or five times normal load. The load is also intermittent owing to opening and closing of the hoppers, necessary in mixing grades of grain.

In warm weather these motors work at about 75 per cent full capacity, while in cold weather they work as high as 20 per cent above rated capacity, due to the effect of the temperature on shafting, journals, belting, etc. In connection with these motors, the question might be asked, " why are not larger motors used?" In the first place the extra cost is to be considered, while in the second place the season for grain handling is generally from the opening of navigation on the Great Lakes until the closing, that is, from the 15th of April until the 5th of Dec., or in temperate weather. The motor capacity for belt conveyers is anywhere from 15 h.p. to 50 h.p., depending on the length of the belt. These belts travel at about 650 feet per minute.

Conveying; *Hopper Conveyer*. From the tanks the grain is directed through a hopper in the bottom of the tank to another belt conveyer, where it is carried out of a tunnel under the tanks, to a bucket conveyer, where it is carried to the garner bins.

Weighing and Shipping. From the garner the grain goes into the shipping bin, mounted on scales and situated directly beneath it. After it is weighed, it goes to the shipping spout and thence to the hold of the vessel. The capacity of the scale is 60,000 lb.

Drying. All grain that is damp has to be dried before shipment. No matter how smutty, damp or dirty it is, it is dried and sold to the miller in that state. The elevator companies used to wash the grain, but it was an expensive operation, considering they got no more for it. The washing bleached it and the value decreased accordingly. Now the mills wash the grain and gage the amount of moisture necessary in the milling process. The defective grain is therefore taken direct to the driers and treated. The drier is a bin generally containing 500 bu. of grain, fitted with vertical sieves and an air chamber, as shown in Fig. 8.

The air chamber is in the center surrounded by the sieves. There is a blank space between each sieve as shown in the cut, and the air circulates in the direction of the arrows. Connected to the drier by an air duct, is a 60-in. fan running at 250 rev. per min. There are two types of driers: hot and cold. The heat is generated by steam. Each heater is made up of 6000 feet of one-inch pipe, and the heat is kept at a temperature of 80 deg. cent. A cold air drier is also operated by a fan, taking a good deal longer than the hot air drier. From the driers the grain is taken to the storage tanks.

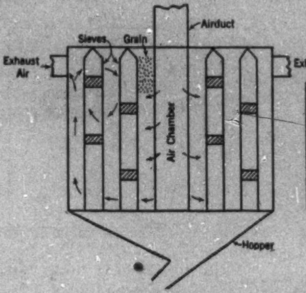

FIG. 8A

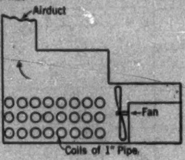

FIG. 8B

Period of Shipping. The grain starts to move as soon as navigation opens and continues rather brisk until the bulk of the grain in storage, in the elevators and cars is shipped. This generally takes until the middle of June. The months of July, August and part of September are slack; and the time is taken advantage of to make repairs, in readiness for the fall rush. This generally starts in the latter part of September (crop conditions govern this) and continues to the end of navigation. This is the busiest season of the year and the peak is established during this period. It is during this time that elevator companies get the best advantage of the maximum demand, as they run full 24 hours. As was before stated, navigation virtually closes, midnight December 5th, as the insurance runs out at that time; but a large number of vessel owners carry their own insurance and continue carrying grain until the canals freeze up.

CONCLUSION

The day load of an elevator is irregular, especially when the process of unloading cars and loading boats is in progress. Fig. 9 shows a typical day load.

The night load, on the other hand, is practically constant, and is the period taken advantage of. During the night there is very little loading or unloading, and the work done is principally cleaning and conveying, the grain traveling in a continual stream. Fig. 10 shows a typical night load.

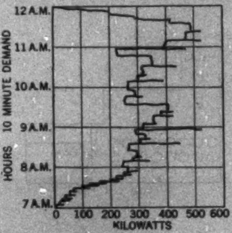

FIG. 9—TYPICAL DAY LOAD FIRST 5 HOURS

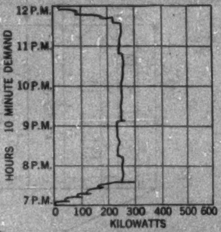

FIG. 10—TYPICAL NIGHT LOAD FIRST 5 HOURS

In Fort William the power factor is maintained at 90 per cent, while in Port Arthur it is 92 per cent.

All the induction motors are squirrel cage type, "protected and self-ventilating." The motors are all protected by fuses and in most cases have a no-voltage release on the auto-starter. As a general rule the motor is either connected to its load by chain or rope drive; a few are belt connected, while a few are geared. The trouble from breakdowns and burn-outs is almost negligible. With the use of vacuum cleaners and compressed air, and the proper care, probably not more than five burn-outs occur in all the plants in one season. The maintenance charges are very small as these plants seldom employ more than two operators each. The operators as a general rule receive $125.00 and $90.00 per month, respectively.

COST DATA OF STATIONS

The cost per kv-a. for the average 22-kv. station, including buildings, transformers, synchronous condensers, high- and low-tension apparatus, is from $37.777 (the lowest) to $42.75 per kv-a.

The cost for a 2200-volt station is from $35.65 to 39.72 per kv-a.

POWER COSTS

As before stated the flat rate charges are $25.00 per h.p., while the maximum demand is figured on the following basis.

Max. demand in kw			280 kw.	
Transformer losses on max. demand			5½ kw.	
Total kw			285½ kw.	
285½ kw	383 h.p.			
Kw-hr. consumption			28140 kw-hr.	
1st 50 hrs.	285½	50	14,275 kw-hr.	
2nd 50 hr.	285½	50	14,275 kw-hr.	
Total			28,550 kw-hr.	
Kw-hr. consumption			28,140 kw-hr.	
Excess			410 kw-hr.	
383 h.p. at $1 per h.p. per month				$383.00
1st 50 hr.	14,275	1.3 cents		189.85
2nd 50 hr.	14,275	1 cent		142.75
Excess	410	0.1 cent		.41
Total				$716.01
Discount 10 per cent				71.60
Charges per month for 280 kw				$644.41

This gives a rate of $27.618 per kw. per annum, but as this bill was the first rendered and the average load per annum of 40 per cent lower, it would be very misleading to quote any figure on the actual cost per kw. per annum.

DISCUSSION ON "FIELDS OF MOTOR APPLICATION" (RUSHMORE), AND "ELECTRICITY IN GRAIN ELEVATORS" (STAFFORD), DEER PARK, MD., JUNE 29, 1915.

THE ELECTRIC ELEVATOR

H. D. James: We often hear engineers speak of the difference in efficiency between electric elevators of the same size, and many of them seem at a loss to understand why this difference exists. It will perhaps be made a little clearer to many of them if we analyze the various sources of loss which occur between the motor and the load, and point out some of the factors which cause a variation in these losses.

The useful work done by the motor is the net load lifted or lowered in the car. In order to equalize the work done by the motor, it is customary to use a counterbalance which is equal to the weight of the car and the average load combined. Sometimes this counterweight is split in two parts, one part known as the car weight, is attached directly to the car, and is less than the weight of the car. The other weight known as the drum weight is attached to the drum and is equivalent to the unbalanced car weight and the average load. The drum weight is wound up on the drum as the car rope is unwound, and vica versa. For smaller installations, the car weight is omitted and all of the counter-balance is attached to the drum. Figs. 1 and 2 show this in diagram form.

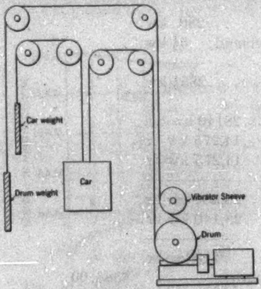

FIG. 1—COMMON ARRANGEMENT HAVING SIX OVERHEAD SHEAVES AND ONE VIBRATOR SHEAVE

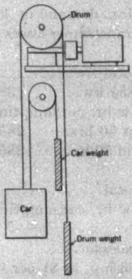

FIG. 2—BEST ARRANGEMENT HAVING ONE OVERHEAD SHEAVE AND NO VIBRATOR SHEAVE

The car and counterweights travel on guide rails attached to the sides of the elevator shaft. The top and bottom counterweights in each frame are usually slotted in the ends and extend around the guide rails. Considerable clearance is allowed and if the weights are properly hung, there is very little pressure on the rails.

The elevator car is usually hung in a steel frame called a girdle. This girdle is provided with top and bottom guide shoes. These shoes are usually adjustable for clearance and are held against the guide rails by springs so as to reduce the vibration of the car. The car is frequently loaded off of center so that at times there is considerable pressure between the guide shoes and the rails. The friction loss between these guide shoes and rails is affected by the material used, the lubrication and clearance of the shoes. The construction of the rails and particularly the joints, may have a considerable bearing on this friction. In well constructed elevators, the total loss from this source can be made quite low, although some cheap elevators using a poor grade of rails, may have considerable loss.

The ropes are usually led over several sheaves before they reach the drum or counterweight. The arrangement of the ropes and sheaves may be a large factor in the total losses. Fig. 1 shows a common arrangement having six sheaves in the overhead work and one vibrating sheave just above the drum. This sheave, in addition to revolving, is allowed to travel horizontally on the shaft, so that it will be directly above the groove in the drum on which the rope is wound. As the rope winds on the drum, it travels back and forth across the face of the drum. Sometimes it is necessary to set the elevator back from the shaft and use two vibrating sheaves, one for the car ropes and one for the drum weight ropes. It will be evident to any engineer that the friction depends upon the number of sheaves, it also depends upon the load on the bearing of the sheave. There is a further loss due to the bending of the rope as it changes from a straight line to a curve in passing over the sheave, and again, as it changes from the curve to a straight line on leaving the sheave. This loss is proportional to the diameter of the rope divided by the diameter of the sheave. For this reason, large sheaves should be used wherever possible.

The arrangement shown in Fig. 2 is sometimes possible and when used, gives the least sheave and rope friction. If the car weight is omitted in the Fig. 2 arrangement, we do away entirely with sheave loss and the only rope loss will be due to the bending around the drum.

Occasionally the rope is led around sheaves so as to bend the rope back on itself something in the form of the letter S. This gives a considerable bending friction on the rope, and, in addition, is very bad for the rope as it causes excessive wear.

With a careful arrangement of sheaves and by using large diameters, these losses can be kept down to a comparatively small value, but it can be readily seen that these losses may be considerable with a poor arrangement.

We have now traced the losses from the car and counterweight back to the winding machine. The winding drum is usually driven by worm gearing immersed in an oil bath. There are a number of systems for cutting this worm gearing. The angle of the worm may also be varied over a considerable range. We can have a single, double, or triple threaded worm. Uusally the greater the angle of the worm, the greater the efficiency. It is, however, the practise of elevator builders to keep this angle small so that the car will not overhaul from rest.

It is very necessary that the worm and worm wheel be accurately machined, and with some systems of gearing, the worm must be very accurately adjusted for meshing with the worm wheel. There seems to be a prevailing idea that the continual wear of the two elements will reduce the friction and improve the efficiency. This is only true to the extent that roughness due to machining may be worn off and the surfaces polished. If the gearing is not correctly cut, the wearing away of part of the material is very unlikely to shape the teeth in the proper way. This is as true of spur gearing as it is of worm gearing and it is a well known fact to those who have made a study of the subject.

The worm exerts an end thrust unless two interlocking worm gears are used. This thrust on the single worm gear must be taken up on a thrust collar, which is often ball bearing or roller bearing; it may, however, be hardened steel disks or bronze disks, depending upon the design of the machinery. The difference in friction between a good ball bearing end thrust and an ordinary disk end thrust is considerable.

Lubrication forms a very important element in the gearing. If the oil is too thin, or is not properly applied, the gears will cut. If the lubricant is too viscous, it causes a loss due to the added effort required to turn the worm. The material from which the worm and worm wheel is made will make considerable difference in the friction.

Manufacturers usually operate the worm gearing before shipment sufficiently to rub off the tool marks and get it in good condition, so that the elevator gearing at the time of installation, should operate near its maximum efficiency.

In selecting a motor to drive an elevator, we must first know the net weight to be lifted and the speed at which it is to be lifted. This gives us the h. p. expended at the load. The total efficiency of the machine is then approximated and the rating of the motor determined. The speed of the motor operating at the above load will be the full load speed of the motor. Some designs of motors have a considerable variation in speed between no load and full load, so that the no load speed of the motor should not be used; this is particularly true of squirrel cage induction motors. The ratio of motor revolutions at full load to drum revolutions is the gear ratio. This fixes the number of teeth in the worm wheel and diameter of drum. Where double or triple threaded worms are used, one-half or one-third of the total number of teeth in the worm wheel should be taken in figuring the gear ratio.

When the elevator car is at rest, it will require about double the running torque to start the load from rest, as the static friction is about double the running friction. The power required to accelerate the load can be neglected unless the speed of the car is high, such as 500 or 600 ft. per min. For low-speed passenger and freight service, the limiting characteristic of the motor is usually the starting torque; the motor being in service for such a small percentage of the time that the heating is not an important feature. The motor that will start the load with the least amount of current from the line is the desirable motor. This desirable starting characteristic is usually obtained at the sacrifice of efficiency and regulation. For higher speed service, these last two considerations cannot be neglected.

Efficiency is not an important item where the operating is infrequent and regulation is not important for low car speeds. In considering speed regulation, it must be remembered that the motor may act as a generator in lowering the load and, therefore, the difference in speed of going down with full load and going up with full load, will depend entirely upon the regulation of the motor. With a car speed of 300 ft. per min. much closer speed regulation is necessary than with a car speed of 100 ft. per min.

The d-c. elevator motor is usually compound wound and the controller is arranged to short circuit the series field winding when the motor reaches full speed. With this type of motor, the speed regulation is very good. The same may be said of the adjustable speed motor which is shunt wound and has a speed variation due to change in the strength of the shunt field winding. The question of regulation seldom becomes important with the d-c. motor when used in connection with a geared machine. Where this motor is used on a direct traction elevator running at 500 or 600 ft. per min., the regulation is one of the controlling features of the design.

For a-c. power, the choice between squirrel cage and slip ring motors is often one of regulation. Either motor can be given good starting characteristics by designing the secondary circuit with the proper amount of resistance. The squirrel cage motor must operate at full speed with this same resistance, so that it has a considerable slip often as high as 20 or 30 per cent. The slip ring motor is provided with a controller for short circuiting the secondary resistance during acceleration, so that the slip at full load may be as low as 3 per cent or 4 per cent. The squirrel cage motor is preferable on account of the simplicity of the controller, but it is limited to low-speed elevator work on account of this large variation in speed.

On account of the secondary resistance of the squirrel cage motor, the full load speed is less and the gear ratio between the motor and the drum must be higher than for the slip ring motor having the same number of poles, in order to give the same car speed. This means that for a given h. p. motor with equal number of poles, the slip ring motor will not be required to develop as much torque as the squirrel cage motor. The squirrel cage motor, however, gives a better torque per ampere input than the slip ring motor on account of the design characteristics. These two conditions about balance each other so that with a properly selected motor and correct gearing, the same load can be started with about the same ampere input to the motor. This analysis is very important as we frequently hear advocates of one motor or the other claim superiority in starting characteristics. Usually the actual results are obscured by the use of improper gearing or by variations in the total efficiency between the motor and the car. It is necessary for elevator builders to have a limited number of gears for each size of machine and the architect is often restricted in his design of the building so that the elevator cannot always be installed for the maximum efficiency. There is also difference in workmanship and materials used so that it is not fair to compare two installations without having analyzed all of the facts.

The problem of stopping an elevator car is much more serious than that of acceleration. The motor may be acting either as a motor or as a generator, depending upon the direction and amount of the load. When the car reaches the top and bottom floors, it is necessary to stop the elevator automatically so that an accident will not occur due to the carelessness of the operator. The distance the car can travel beyond these floors is called the overtravel and is usually very limited. With low-speed elevators it is not difficult to stop the car as the energy required is proportional to the square of the speed. When the d-c. motor is used, a fixed low speed can be obtained by strengthening the field of the motor and by placing a shunt resistance around the armature. The motor is also used as a generator for dynamic braking in bringing the load to rest. This enables the engineer to apply the d-c. motor to high-speed elevator service with excellent results. The d-c. elevator has been used for the longest travel elevators installed, operated at the highest speeds; in fact, there are installations where only an electric elevator could be used.

The use of an a-c. motor for high-speed elevator service has presented a difficult problem. The motor as usually built, has only one fixed speed. The car must, therefore, be brought to rest by the mechanical brake from the maximum speed. This places a limit upon the speed of the elevator. Elevators of this kind are usually limited to 200 ft. per min., although higher speeds have been used in some instances. Recently, some induction motors have been built having two sets of poles in the primary; one set of poles for full speed and one set of poles giving one-third speed. The secondary also has two sets of windings. This enables the engineer to arrange for a fixed low speed from which to make his stops and has materially increased the limit of car speed for which an induction motor-driven elevator can be used.

To summarize: The total efficiency of electric elevators may vary over a considerable range, from as low as 25 per cent to over 75 per cent, depending upon the design, workmanship and arrangement in the building. The losses may be separated under the following headings:

1. Friction of car and counterweight on guide rails.
2. Bearing friction of sheaves.
3. Bending friction of ropes.
4. Efficiency of worm gearing.
5. Efficiency of electric motor.

Item 5 affects the power bill only and is not important where the operation is infrequent. Items 1 to 4, inclusive, influence the size of motor used as well as the power bill. It is to the advantage of the purchaser to keep down the size of his motor. A large motor is less efficient on average loads, and increases the strain on the machinery and the first cost of the elevator.

INDIVIDUAL MOTOR DRIVE AS USED IN THE OIL FLOTATION PROCESS

W. M. Hoen: One of the most important of the latest applications of motor drive as applied to the metal mining industry is found in the oil flotation process. There are several variations of the flotation process in use, but this application refers specifically to the mechanically agitated type as used in copper and zinc mining.

In the treatment of copper ores the solutions are generally worked cold, while in treating zinc ores it is found advisable to work the solutions hot. Due to the violent agitation the air above the tank is always filled with a very fine spray. In mills using the hot solution method the air is heavily laden with moisture, unless removed by fans.

The tanks or cell boxes are approximately 2 by 3 feet and are assembled in groups of from 8 to 16, depending upon the class of ore being treated. During the development of the process crossed belts constituted the original method of drive. They were successful for the small experimental machines but when applied to commercial work were not satisfactory. In the zinc mills, due to the excessive moisture, they were found to be an absolute failure. The next step was to use a bevel gear driving each cell of the unit from a common shaft. In practise this method was partially successful but a great many difficulties were at first encountered. The friction losses were high until cut gears were used, which were completely enclosed so as to run in oil. The thrust caused by the weight of the gears, shafting and propeller caused considerable trouble. Any slight difficulty with one unit which would cause a shut-down, reduced the mill tonnage by an amount equal to the output of the total group of cells. Expensive thrust collars of the ball bearing type were sometimes used in order to improve the mechanical operation. About the end of 1913 this process was so well advanced that the mill operators decided that a more efficient and flexible system of drive was advisable.

Practically all of the agitators in successful operation were running at a speed of 265 rev. per min. The application of vertical motors, one to each tank, appeared to be the best solution. However, practically all of the metal mines in the West have 60-cycle power, so that a direct-connected motor to run at this speed is almost an impossibility, from a design and commercial standpoint. The original process started out with an agitator running at about 3 rev. per min. Development had brought this speed up to 265 rev. per min. and the only apparent reason for this definite speed was that with the design of propeller in use the most efficient results were obtained at this speed. Experiment had shown that each tank would require between 7 and 10 h.p. A three-phase induction motor built for this rating at 60 cycles does not give good performance nor reasonable manufacturing costs if built for more than 12 poles. It was decided that a 12-pole motor of the vertical type would be the best proposition as standard parts would be available. This meant that the agitator must run at a speed of 570 rev. per min. The problem now was for the metallurgists to devise an agitator cell and propeller which would give the desired results at this speed. These results were very successful and this speed has now become practically standard.

The motor as finally applied consisted of standard vertical parts with a special sub-base and bearing. This sub-base was designed in conjunction with the agitator cell. The lower bearing was practically a standard although of extra large size. The shaft is threaded so as to take a screw coupling and the propeller is mounted on a short piece of shaft which is coupled to the motor shaft and prevented from locking by a small block. This makes a very strong, compact and simple construction so that an additional bearing is not required. The vertical bearing must be capable of supporting the additional weight of the propeller, its shaft, and a downward thrust due to the action of the propeller. The excessive moisture condition made it advisable not to permit circulation of the air from the top of the tanks up through the motor windings. This was prevented by providing an enclosing plate in the sub-base. In a motor of this rating and number of poles, its over-all size is such that nearly all of the heat due to the losses is given up by radiation and not by convection. In order to prevent injury to the windings during periods of idleness it was necessary to impregnate them with a moisture-resisting varnish. Each bearing is lubricated independently; the oil inlet pipe for the lower bearing is cored in the base. A pipe, as ordinarily used, would be quickly destroyed by action of the metallic particles.

The design of agitator cell and propeller finally adopted requires 10 h.p. when operating under normal condition. A change of metallurgical conditions will cause this to vary from 7 to as high as 20 h.p. However, it was found that with these changes in h.p. the metallurgical results also varied. The most desirable range was found to be such, that a motor with a normal rating of 10 h.p. would have to carry 25 per cent overload continuously and 50 per cent overload for short periods without reaching dangerous temperatures. This overload condition only applies to the motors in the series which do the preliminary mixing. Some cells are grouped for rougher service, separating the higher values, the tailings being reground and treated in the finisher cells which give the finished product. However, no appreciable saving could be effected by making the motors of different capacity, as any saving would be offset by the advantages of having all motors duplicates.

This process has taken great strides in the last year and a half, so that several hundred agitator cells are in operation. At first sight it might seem that the application of individual motors is a very expensive method. Some of the most important advantages are as follows:

(1) Each cell is a unit so that one cell may be shut down with only a relatively small reduction in mill tonnage.

(2) Mechanical difficulties due to gears, many bearings, shaft alignment and the hazard from belts is entirely removed.

(3) The operation of each cell can be easily checked by the power consumption.

(4) In the majority of these plants the cost of power is the smallest item, continuity of service and reliability of operation are of the greatest importance. In metal mining the use of any particular method of drive or type of apparatus is simply a means to the end, as the object of the mine and mill is to produce metal.

(5) The results obtained from the metallurgical end are such a great improvement over the water concentrating methods that the total mill equipment required is actually less and the labor required to handle a given tonnage is reduced. Although this process is now being used chiefly to recover values from slimes, which values were formerly lost, there are indications that it will be used for the total recovery of certain classes of ores.

The unit drive has proven very successful and shows what success can be obtained by the close cooperation of the electrical and metallurgical engineers in solving an apparently simple but complex power drive.

FRACTIONAL HORSE POWER MOTOR APPLICATION

H. F. Boe: Small motor applications fall into four classes depending upon the operating period and the variations in load.

1. Continuously operating motors with approximately constant load.
2. Continuously operating motors with varying load.
3. Intermittently operating motors with approximately constant load.
4. Intermittently operating motors with varying load.

It is usually impossible to obtain data by correspondence sufficiently accurate and complete to permit an engineer to calculate a suitable motor to drive a certain machine or device, on account of the peculiar characteristics of the machines themselves as well as the extreme variations in operating conditions while in service.

Most small motor-driven machines are manufactured in quantities sufficiently large to warrant careful tests to determine the application. A sample motor with electrical characteristics approximately those required is generally used to analyze the application.

Owing to the policies followed by central stations, 110-volt, 60-cycle lighting circuits are nearly universal and motors of the split-phase type are used to a considerably larger extent than any other type of small motor. This type of motor is generally used for test purposes.

Tests. The main readings to be taken on test are:

1. Volts.
2. Amperes.
3. Watts.
4. Speed of motor.
5. Speed of machine.

These should be made for each of several loads, enough readings being taken to represent all actual operating conditions.

A very careful analysis should be made of:

1. Starting condition
2. Normal and maximum load conditions.
3. Cycle of operation.
4. Length of operating period.
5. Method of drive.
6. Peculiar mechanical or electrical characteristics required.

Starting Torque. The torque required to start the machine under normal and maximum load conditions must be definitely determined. This can be obtained by reducing the voltage at the motor terminals to a value just sufficient to start the machine and bring it up to speed. By substituting a Prony brake and a scale for the load and measuring the locked torque of the motor at the voltage obtained above, the actual starting torque is obtained. This is usually expressed in ounces at one-foot radius.

Normal and Maximum Torque. The normal load torque can be obtained by means of a brake test on the motor at the same input found under actual operation of the machine at normal load. The maximum torque can be determined in the same way if the maximum load is of sufficient duration to read the motor input. If this is not the case it can be obtained by reducing the voltage at the motor terminals to a value just sufficient to carry the maximum peak load. By substituting the Prony brake for the load and measuring the pull-out torque of the motor at the reduced voltage obtained above, the actual maximum torque is determined and is expressed in the same terms as the starting torque.

TEMPERATURE

The temperature rise of the motor for normal operating load should be determined by actual test and the overload conditions and the possible temperature rise under overload taken into consideration. Where feasible these heat runs should be made in connection with the driven machine, since this method more nearly gives the actual operating temperature. However, where this is not feasible, temperature test on the motor may be taken in some more convenient way and still approach operating conditions.

METHODS OF DRIVE

The method of drive determines largely the speed of the motor selected and likewise the mechanical characteristics of the frame, brackets, shaft and bearings, and therefore is of vital importance in the application of the fractional horse power motor.

Belt. Where round or flat belts are used the ratio of pulleys should be such that the motor pulley will be of normal size. The distance between pulley centers should be great enough to eliminate excessive belt tension, or if this is impossible an idler pulley should be used. Small motor pulleys and short belt centers are sometimes used successfully on very small machines where the load and starting conditions are comparatively light, but ordinarily idler pulleys are desirable where the pulley ratio is large and the distance between the belt centers small.

Spur Gears. Numerous small motors are connected to the driven devices by means of spur gears. This gives a very positive drive and excellent results are obtained. In general, it is desirable to keep the gear ratio 5 to 1 or less, but some small motor driven machines use successfully gear ratios considerably in excess of this. A careful analysis should be made of limiting pinion sizes before gear ratios exceeding the above are used.

Bevel Gears. If the motor drives the machine through bevel gears the best results on small machines seem to be obtained where a ratio of 2 to 1 is not exceeded. However, in some cases ratios as high as 3.5 to 1 have been used successfully, depending on method used in manufacturing gears. This drive is positive, but there is always some end thrust which must be taken care of in a way which will not cause undue wear on the motor bearings.

Silent Chain. If large reductions in speed and only a short space between motor shaft and machine shaft is available, a silent chain drive may work admirably, since large ratios of sprockets and short chain centers are permissible. This makes a very good positive drive.

Worm Gear. Worm gear drive is used extensively and large reductions in speed are obtained. Where this drive is encountered care should be taken to see that the worm thrust is properly taken care of. In general, the worm should have its own thrust bearings which must be large enough to take a thrust equal to the maximum torque of the motor.

Friction. Where friction drive is used careful measurements of the thrust on the motor shaft should be made. If any thrust is found it may be necessary to equip the motor with special thrust bearings. This method of drive is used largely where it is desirable to get an adjustable speed with a constant speed motor; for example, moving picture projecting machines.

Direct Connection. When motors are to be directly connected to the load the method of mounting should be noted. The distance between center line of shaft and base should be determined and the amount of permissible variation specified. The distance from center line of motor to end of shaft extension, the length and diameter of the shaft extension and whether the motor has to take care of end thrust must also be investigated. This method of drive is being used with excellent results. Sometimes rigid couplings are used, but in general, flexible couplings are more desirable.

MOUNTING

A careful analysis should be made of:

1. Method of drive.
2. Method of mounting—Is motor to be arranged for floor, wall, ceiling or vertical suspension?
3. Location of the motor with respect to machine it drives.
4. Limiting space available for the motor.
5. Limiting manufacturing dimensions in regard to distance from center line of shaft to base, and center line of motor to end of shaft extension.

CHOICE OF MOTOR

A-C. Single-Phase. Having determined the mechanical and electrical characteristics of the motor required to drive successfully the machine in question, there are various other features to be taken into consideration before definitely recommending a motor.

An allowance must be made for:

1. Variations incident to manufacture of machines in quantity.
2. Variations incident to manufacture of motors in quantity.
3. Minor variations in voltage.
4. Minor variations in frequency.

Since the torque of a motor at starting varies approximately as the square of the voltage, it is imperative that a motor be selected that will start against the worst possible conditions. This is due to the fact that they are generally connected to lighting circuits where insufficient transformer capacity or light wiring will cause the voltage to drop considerably at times, particularly when starting. This voltage may be reduced to possibly 80 per cent of its rated value, the starting torque of the motor then being approximately only 64 per cent of the torque at full voltage.

The maximum torque of the motor selected must be sufficient for the worst load condition to which the machine will probably be subjected at a voltage at least 10 per cent below normal rated voltage.

The motor should be capable of operating on a circuit with a variation of 10 per cent plus or minus in frequency, 10 per cent plus or minus in voltage, or an equivalent combination of voltage and frequency.

No-Clutch Motors. Under light load starting conditions and where the motor runs for long periods of time at constant load, motors without clutches should be used. Motors rated ⅙ h. p. and below are usually built without clutches, since reasonable starting torques are obtained without objectionable starting current.

Clutch Motors. Clutch motors are designed so that when starting, the rotor revolves freely on the shaft. When nearly full load speed is reached the clutch operates automatically by centrifugal force and engages the shaft through the clutch. With a properly designed clutch the load is then accelerated smoothly and without shock. This type of motor develops practically maximum torque at starting and requires starting current which is less and also of shorter duration than in the no-clutch motors. (See Fig. 2, Mr. Lester's paper.)* It is desirable to use clutch motors where high starting torque is required and particularly so when high starting current is objectionable.

Repulsion Induction Motors. Repulsion induction motors should be applied where the initial starting torque required is very high and the torque drops off very rapidly during acceleration. At the instant of changeover from repulsion to induction running the torque does not exceed a small fraction over full load torque. A typical application of this motor would be a deep well pump. (See Fig. 1, Mr. Lester's article.)*

Odd Frequency Motors. Having selected a suitable 60-cycle motor, it may be necessary to line up suitable motors to operate the machine on other frequencies from 25 to 133 cycles since lighting circuits of other frequencies are sometimes encountered. If these motors are to drive the machine at the same speed as the 60-cycle motor and proper gear or pulley ratios are made to take care of the variations in speed of the odd frequency motors, it is necessary to furnish proportionate torques on these machines. If it is the intention to use the same pulleys or gears, the motors will have to have the same torques as the 60-cycle, which in some cases will increase the horse power while in others it will decrease the horse power of the motor, depending upon the number of poles and the frequency of the motor.

D-C. Motors. Having obtained the characteristics of the a-c. motors the d-c. motor should be selected having as nearly the same mechanical characteristics as possible.

Shunt-Wound Motors. If the motor starts with light load and runs at practically constant speed with constant or variable load, a shunt-wound motor should be used.

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Compound-Wound Motors. If high starting or maximum torque is required and a slight variation in speed with variations in load is permissible, compound-wound motors should be used. Usually motors below ⅛-h.p. can be supplied shunt-wound.

Series-Wound Motors. Where exceptionally high starting torque is required, where the load is constant or where a large variation in speed with a small variation in load is permissible, series-wound motors should be used. Series-wound motors, however, should always be connected to the load through a positive drive.

Universal Motors. The so-called universal motors are designed to run on either alternating or direct current and have series motor characteristics. These motors are high speed and used almost exclusively on portable electric drills and small fan type vacuum cleaners.

Open or Enclosed Motors. If motors are to be used in a damp or dirty place, where they may be subjected to water, acid fumes, or where they are in close proximity to inflammable material, they should preferably be enclosed. It is desirable to mount all motors where they get the maximum amount of ventilation.

PRINTING PRESSES

Wm. C. Yates: In the printing industry, the electric motor finds a most important field of application. In fact, the motor is indispensable, as it furnishes the ideal drive for the various machines in a printing plant which in no modern establishment or one of any consequence are operated by any other means. The chief factors favoring motor drive as compared to any other driving means are:

No obstruction to light by overhead belting and shafting.
Cleanliness.
Quietness.
Convenience of location.
Saving of floor space and headroom.
Economy of power.
Wide range of speeds.
Convenient control.
Protection to the operator.
Economy of time—Reliability.

These factors may be recognized as applying to almost any kind of machinery equipped with individual motor drive. There are no machines, however, to which the speed range, convenience of control, and reliability of the electric motor are of greater importance than to a printing press, especially one producing a daily newspaper.

In the general book, pamphlet and job printing industry motors are applied to composing machines, printing presses, folders, cutters, stitchers, and binding machinery. In newspaper printing plants, motors are used on composing machines, matrix and plate making machines, printing presses, paper hoists and conveyers and exhaust fans. For all machines with the exception of the presses and folders the selection of a suitable motor is a relatively simple matter and no special features of control are involved. For the most part, constant speed motors are employed and the control may be an ordinary hand starter or in cases where remote control is desired, a self starter may be used which is operated from one or more push button stations. Where the work necessitates the use of an adjustable speed motor, a manually operated speed controller will usually answer the purpose.

The advantageous characteristics offered by the electric motor apply to all the power driven machinery in the printing plant but especially to the presses, which require features of drive and control that nothing else can offer. In the following are taken up the several broad classes of printing presses, with a brief discussion of the types of motors applicable in general to each class and of the features entering into the proper control of the motors.

The various types of printing presses fall into three general classes:

Small platen presses, ordinarily called job presses.
Flatbed cylinder presses.
Rotary presses.

Job Presses. These, used for printing cards, circulars, small jobbing and commercial work, have a type bed and impression platen which are both flat surfaces. The type form is held stationary, and approximately vertical, while the platen on which the paper is placed swings up to meet it. Hand sheet feed is the rule, though automatic feeds are sometimes used.

The general run of job presses require motors ranging in capacity from ⅛ to 1½ h. p. The motors are generally best mounted on the floor and arranged for belt drive to a fairly large press pulley. Friction drive, using a friction pulley bearing against the flywheel, is also used.

The control requirements are simple. On d-c. circuits a shunt motor is employed usually controlled by a no-voltage-release speed regulating rheostat in the armature circuit. The small sizes of the motors used make permissible control of speed by armature resistance as the wastage of power is inconsiderable, especially as the motors are usually run at or near normal speed.

There are applications, where the speed of production is of prime importance, where a push-button-operated controller, providing predetermined speed setting, gives the best results.

On a-c. circuits the best results are obtained by the use of a commutator type single-phase motor. Such motors are available, designed for speed control by brush shifting and with the shifting mechanism arranged for foot operation.

Flatbed Presses. These have the type forms carried by a heavy, rigid platen sliding back and forth in "ways," similar to the bed of a metal planing machine. At each pass the type passes under the impression roll at one end of its travel, and under the inking rolls at the other extreme. There are several classes of flatbed presses differing in the relative motions of the cylinder and platen, although in all types the impression cylinder always revolves in the same direction.

Flatbed presses are employed for sheet printing and are generally used for color work. The feed may be either hand or automatic.

The ideal location for motors is within the frame of the press, on brackets. Belt drive is preferable to gear or chain drive as the slipping of the belt serves as a protection against shocks to the motor and machinery. The motors required range in capacity, for different makes and sizes of presses, from 1½ to 15 h. p., and must be capable of exerting a strong starting torque, for which reason the d-c. motors are usually compound-wound with about 20 per cent series field. The a-c. motors used are for two or three-phase circuits and are of the slip ring type.

The ordinary requirements of speed variation are met by providing the d-c. motor with 50 per cent reduction by armature resistance, and with field control giving a 25 or 50 per cent speed increase above normal. In the case of the a-c. motor, regulating resistance is furnished which permits of a speed range down to 50 per cent of normal. Ordinarily only the higher speeds are in requisition, the lower speeds being required for occasional jobs where an extra high grade of work is involved.

The ideal control equipment provides for push-button starting and stopping and for predetermined speed control. The ability to start or stop the press from stations at both the feeding and delivery ends makes for greater convenience and safety to the operator and is an important factor in the saving of time. The predetermined speed feature makes possible the proper setting of the ultimate speed for the work in hand so that when the press is producing it will run at that speed. Thus is avoided the wasting of time by reason of running too slow, as also the spoiling of work from running too fast. Furthermore, it becomes possible to work to a definite schedule of production, which is of great importance to the printer.

Other features of the control equipment are:

No-voltage protection to motor and to operator.

Overload protection to the motor.

Dynamic brake or solenoid brake for quick stopping.

"Jogging" or "inching."

Reverse for emergency conditions only.

Recent developments in control equipments for use with a-c. motors incorporate all of these advantageous features. The essential difference is that dynamic braking is, in the nature of things, out of the question, and a solenoid brake is used. The results, however, are identical.

Lithographing Presses. The lithographing press differs from the ordinary flatbed press in that it prints from an engraved stone instead of from type. In its various makes and sizes it takes motors ranging in capacity from 2 to 10 h. p. The requirements as to the types of motors, speed range, and control features are the same as for the general run of flatbed presses.

Rotary Presses. Rotary web presses, used largely for magazine or newspaper work, employ curved stereotype, electrotype, or zinc printing plates, attached to the cylinders. They print a continuous roll or web of paper, which allows a much faster speed than even the automatic feed applied to flatbed presses. Due to this feature, and also to the elimination of heavy reciprocating parts, this type of press is superior in point of speed.

Small rotary presses, which may print either on a continuous roll or on automatically fed sheets, are used for work similar to that performed by job presses and flatbed presses. The motors required range in capacity from 2 to 15 h.p. and the types of motors and the control features are essentially the same as for the job and flatbed presses doing similar work.

Rotary Magazine Presses. The sizes of rotary presses used for magazine printing require motors ranging in size from 5 to 35 h.p. The d-c. motors employed are compound-wound and of the adjustable speed type with speed range by field control of 2:1, although occasionally a speed range as high as 3:1 is of advantage where the work which the press turns out is of widely varied quality. When a-c. motors are used they are of the slip ring type with speed control by resistance in the secondary circuit.

A suitable control equipment may be either "full automatic" or "semi-automatic," although the former is the more convenient to the press operators. By "full automatic" is meant entire control from push-button stations. Each complete master station, of which there may be one or more, contains push-buttons for "jog," "fast," "slow," "stop," and a two-button-operated snap switch for "safe-run." Partial stations, of which there may be several, usually comprise "jog" and "safe-run".

The various contactors and other remotely controlled switching mechanisms actuated by the push buttons are mounted on a panel together with the knife-blade line switches, fuses and whatever instruments may be desired. The panel and resistances connected thereto may be placed in any available space as the complete control of the press is accomplished from the stations and the only devices on the panel ever manually operated are the line switches.

Pressing the "jog" button will cause the press to run at a very low speed as long as the button is held closed. When the button is released the press instantly stops. Pressing the "fast" button will start the press off at the lowest speed and gradually accelerate it toward the highest running speed as long as the button is held down. When the "fast" button is released the press will run at whatever speed it has attained. Pressing the "slow" button causes the press to decrease in speed. The "stop" button is used to bring the press to a quick stop. The "safe-run" buttons permit of opening the control circuits at any one station so as to prevent the starting of the press from any other station.

Whether the press be stopped by release of "jog" button or operation of "stop" or "safe" buttons, the brake comes instantly into effect and quickly brings the machinery to rest.

A "semi-automatic" control equipment differs from the "full automatic" in having a manually operated device for bringing the machinery up to running speeds. The "jog," "stop," and "safe-run" features are, however, controlled by push-buttons exactly as in the "full automatic" equipment.

The equipments for induction motors accomplish much the same results as those for d-c. motors. The advantage in favor of the d-c. motor lies in economical producing speeds over a wide range. When the producing speed is to be at or near synchronous speed the induction motor offers no disadvantage whatever.

Rotary Newspaper Presses. The great advantages of motor drive as compared to any other drive in the case of rotary presses lie in:

Economy of space—Crowded conditions usually prevail in a newspaper plant.

Convenience of control—From several stations and by quickly operated devices.

Safety—All is hurry and bustle and the press operators must be protected against carelessness.

Delicacy of control—The web of paper must be slowly fed in while making ready and gradually accelerated to the full running speed.

Reliability—The loss of an edition is a serious matter.

Some small newspapers are produced by single motor-driven rotary presses in which case the equipment is the same as described for the rotary magazine presses.

The larger newspapers, however, are run off from rotary presses which have a two-motor drive. A small motor is used driving the press through gearing to obtain the make-ready, low speeds. A large motor is used to obtain the high producing speeds. When the large motor takes up the work the small motor is electrically and mechanically, automatically disconnected.

The motors required range in capacity from a 3+25-h.p. to a 10+100-h.p. combination. A speed range of 2:1 by field and 50 per cent reduction by armature is usually provided in the large motor of the d-c. combination. The running speed range of the induction motor combination is from normal down to about ½ normal. In either case the ordinary producing speed is usually figured at about 75 per cent of the ultimate possible speed in order to allow for contingencies of delay.

The control equipment for the two-motor drive is almost always of the "full automatic" type and the same features of control are incorporated as already described. The push button stations are the same as for single motor drive, but the control panel naturally contains a larger array of devices by reason of the fact that both the small and large motor must be controlled and in proper sequence.

A modern newspaper press room equipment may use two-motor a-c. drive. The press may be quadruple or double 16-page unit, capable of printing 30,000 16-page papers or 15,000 32-page papers per hour. Some large newspapers necessitate two, four, six, and even eight press units. Producing speeds vary from 20,000 to 36,000 papers per hour, of 12 pages per paper up to 32 pages. Presses even larger and faster have been built.

MOTOR APPLICATIONS OF THE BRICK MANUFACTURING INDUSTRY

T. Z. Simpers: The brick manufacturing industry, including building, paving, ornamental and fire brick, tile, sewer pipe, etc., has an annual production of $200,000,000 in value. Approximately 100,000 h.p. is required to make this product, which signifies the importance of the industry from a power application standpoint.

Brick manufacturing plants are located in all parts of the country supplying product for local consumption, and there are few central stations that do not have one or more, either as customers or prospects. The load offered by these plants is attractive to central stations, on account of the fact that during cold weather the brick plant is usually shut down, meaning that the power requirements occur mainly in the summer, when the central station load is otherwise at its lowest point. Owing to the fact that the power requirements for brick plants are small, ranging from 75 to 500 horse power, and consequently the generation of their own power rather costly, power can usually be purchased to good advantage.

The general conditions surrounding the application of motors in brick manufacturing plants are among the worst encountered in any industrial service. These unfavorable conditions are:

1. Severe starting requirements—due to inertia of driven machinery and to material in machinery hardening when at rest.
2. Severe overloads—due to irregular feed of material.
3. Dusty atmosphere about plants and presence of dampness, causing collected dust on the motors to become cemented to the windings, resulting in insulation strains and interference with ventilation.
4. The use of gears of large pitch and high pitch line speeds resulting in severe vibrations.
5. Lack of careful and intelligent inspection of machinery.

Good service is obtained with these conditions only when careful consideration is given to the application of each individual machine. Before deciding on the motor size, type, and method of connection to the clay working machines, it is important to analyze the following points:

1. Starting conditions, including the amount and variation of torque required and the frequency of starting.

2. Running conditions, including general nature of work to be performed and the variations in load for various rates of production.

3. Mechanical conditions of application.

It is necessary that motors applied in brick manufacturing plants should have generous starting and running characteristics, bearings dust-proofed, windings impregnated against moisture, The motors should be carefully installed with respect to alignment with driven machines, and drive connecting to same. The requirements vary greatly in different plants, and are materially affected by the general design of the plant, methods of operation, and the nature of the material worked.

To provide for the severe starting and running conditions, there is a tendency to select motors larger than necessary. The result of the low load factor caused thereby is low power factor and low efficiency of the individual motors.

The advantages obtained by the application of motors in brick plants are briefly as follows:

1. *Economical Arrangement of Plant.* The various departments of the plant can be arranged to the best advantage by the application of individual motors or motors driving small groups of machinery, which is in contrast with the complicated arrangement required by a single driving unit.

2. *More Efficient Operation.* This is accomplished by the reduction of losses in line shafts and belts and by the restriction in operation to those machines actually required by the work.

3. *Protection against Dangerous Overloads* of driven machinery afforded by simple control.

4. *Increased Output.* This is accomplished by the greater continuity of service, and the constant speeds of machinery afforded by individual drive.

One of the points of importance in the consideration of the change over from steam to electric drive is the method of drying the brick. In those plants where heat exhausted from the kilns is used for drying the brick, or where drying tunnels are heated directly by coal or gas, no change is necessary. However, when exhaust steam is used, it will probably be of advantage to consider some other method of drying, in order to eliminate the use of boilers for this purpose only.

While in some cases water or oil is used for lubrication of the die of the brick machine, in some plants the use of steam for this purpose has proven of advantage and in such cases, can be secured by a small boiler located adjacent to the brick machine.

The decision must be made as to whether group or individual drive of machinery would be the better. For plants with storage facilities between the various departments, and the machinery scattered, individual drive will usually be of better advantage, while for plants with all machinery inter-dependent and grouped, group drive would be better.

A-c. motors are almost without exception used by clay working plants, because of the extensive use of central station power. This type of motor possesses the advantages of greater simplicity and less parts to be damaged by dust and dampness as compared with the d-c. motors.

The progress of material through a brick manufacturing plant involves the following applications.

Hoist or conveyer from quarry to plant.

In large plants, with a long haul, the clay is transported by an industrial railroad. An economical method is by means of a motor-operated transfer car or locomotive, which may be operated by alternating or direct current from overhead trolley. The loose material and large amount of dirt around a plant of this kind, makes the third rail system undesirable.

The material may be dumped into storage bins or conveyed direct to crushing or disintegrating machinery after reaching the plant. In case the raw material is shale or rock, crushers and dry pans are usually used, while for soft and stiff mud, refining rolls or various forms of pulverizers are used.

Where the material is located a short distance from the plant, a convenient arrangement is to control the hoist or conveyer and the crushing machinery from the same point.

The usual drive for the conveyor from the storage is by belting from the motor driving the crushing machinery, although in some cases it is more convenient to use an individual motor.

Crushing machinery is usually of such type that belting is the most suitable method of applying motors, although some types of crushers operate at suitable speeds for direct coupling of the motors. Motors with good starting and pull-out torque characteristics are required by all types of crushing machinery.

Dry pans are usually driven by constant speed motors geared to the dry pan shaft. The vibration of this machine is very severe and it is advisable that the motor shaft be rigidly supported by an outboard bearing. It makes an improved arrangement to provide a flexible coupling between the gearing and the motor as this prevents the transmission of vibration to the motor to a large extent. This is especially important with respect to d-c. motors.

An arrangement for dry pan drive has recently been proposed whereby the motor is mounted on the top of the pan, and the motor shaft is rigidly supported by a pedestal bearing mounted upon the frame. Such an arrangement is very compact and should mean a reasonable life to the motor.

The pug mill and auger machines may be driven by motors belted or geared to the respective machines. Because of the large pitch of gears of these machines, considerable vibration results, and flexible couplings should be used if the motors are geared. The auger machine will require more power than any other machine in the plant and may require one-third of the total. In making this application, careful consideration should be given regarding the starting current taken by the motor and the capacity of the power plant. If there is no clutch between the motor and the auger, the motor will be required to start frequently, and if the current taken by this motor is near the capacity of the power plant, serious trouble from plant operation may result, due to excessive drop on the line voltage. In smaller capacity machines, the pug mill and auger are often combined in one unit, in which case, belting is the usual method of drive.

The cutters, represses and conveyers between the various machines require little power and may be driven from the motors driving the machines upon whose operation they are dependent, or individually by small motors.

When individual drive is used, the motors are as a rule, geared to the driven machinery, offering the advantage of less space required and lower maintenance costs. For machines which are started without load and are driven by motors 50 h.p. or smaller in capacity, squirrel cage motors will give satisfactory operation.

The operation of the pug mill and auger machine is practically constant, but an occasional stop is necessary. Under these conditions, the machines will be full of material which hardens if the shut down is of appreciable length, and if the machines are not provided with clutches, the starting requirements on the motor are severe. For such installations, a wound rotor motor is advisable.

Motors for blowers and exhaust fans will be required according to the type of kilns and method of drying used. These machines are required to operate 24 hours per day and for these applications, central station power can be used to good advantage, as it eliminates the necessity of the operation of an auxiliary engine at light load at night, as required by engine drive.

The power requirements for making brick vary considerably with the kind of material used, the product made, and the methods used for obtaining the product and to approximate the power required per unit output, is only possible after the layout of the plant is made.

The table on the following page gives an outline of the output and power requirements of a number of brick manufacturing plants.

It is to be noted that the soft mud plant making common brick requires the lowest amount of power for production. This is due to the fact that little crushing of material is required. The stiff mud plant requires considerably more power than the soft mud plant, due to increased power for crushing and the power requirements of this type of plant vary greatly, according to the hardness of material.

Considering the power requirements of the individual machines, tests have shown that 35-40 h.p. is sufficient to drive a 9-ft. dry pan, when working at full capacity. The dry pan is the most usual grinding machine used in stiff mud plants. The power requirements of auger machines vary considerably, according

Type of plant.	Capacity per day	Output per day	Kind	H.P. installed.	No. of motors.	Source of power.	Method of drying.	Kw. hour per 1000	Average kw. hour per month.	Load factor 24 hours	Remarks.
Soft Mud	96,000	...	Common	225	3	C. S.	Air	10.5	21,020	17.7	Output varies with time of year.
Stiff Mud	60,000	14,400	Common	185	3	C. S.	Drying tunnels	32	14,400	14.8	Waste heat and slack coal are used to heat tunnels. Monthly av. for only 3 mos.
Stiff Mud	60,000	30,000	Common at time of test.	175	5	C. S.	Waste heat	23	17,000	18.4	Av. kw. per mo. found from daily kw.
Stiff Mud	45,000	30,000	Common	100	1	C. S.	Steam heated tunnels.	24.4	18,697	35.2	Monthly average taken from test for 1 month, but seems to be average month.
Stiff Mud	....	15,000	Common	125	2	C. S.	Waste	23	8,721	13.3	
Stiff Mud	....	35,000	Common	147½	3	C. S.	Waste	12.8	11,248	14.5	
Press	....	45,000	Press brick	10	1	C. S.		10.8	489	9.25	
Stiff Mud	....	20,000	Press	50	1	C. S.		3.8	1,924	38.4	
Soft Mud	....	250,000 month	Common	56	5	C. S.		7.6	1,880	6.4	From test of one month.
Stiff Mud	....	....	Hard	105	3	C. S.			6,825	12.3	For four months.
Soft Mud	....	33,300	Common	75	1	C. S.		5.9	4,854	14.7	Runs off peak, runs about 5 months per year.
....	....	40,000	Common & Repress	126.5	7	C. S.		14.8	9,756	14.7	
Soft Mud	....	30,000	Common	40	1	C. S.	Air	1.5	1,092	5	Only runs part of year.
....	....	....	Refractory & firebrick	270.5	14	C. S.	Air	....	23,506	16.5	
Soft Mud	....	40,000	Common	100	2	C. S.	Air	4.7	3,696.6	7.0	
Soft Mud	....	40,000	Common	60	2	C. S.	Air	5	4,310	13.6	
Soft Mud	....	40,000	Common	182½	9	C. S.	Waste	5.8	5,758	6	(Only operate 3 or 4 months per year.)
Stiff Mud	60,000	25,200	fire brick	168	7	C. S.	Air	28.5	16,386	18.5	(Have 20-h.p. gas engine on fan.)
Stiff Mud	30,000	....	Common	100	1	C. S.	Air	8 to 12			
Stiff Mud	350,000	230,000	Common	888	18	C. S.	Air drying tunnels.	12.7	72,248		List motors includes 75 h.p. on m-g. set furnishing d.c. for 11 motors on trucks, etc.

to their size. For machines of capacities up to 7500 bricks per hour, 10 h.p. per 1000 bricks per hour is approximately required, while for the larger machines of capacities, 25,000 to 40,000 bricks per hour, 5 h.p. per 1000 bricks per hour would seem ample. The pug mills will require approximately one-half of the power required by brick machines of the same capacity. The conveyors about the brick plant are a simple mechanical proposition, as to power requirements, although 50 per cent should be added to the calculated power requirements in order to take care of the friction losses. The h.p. requirements of fans and blowers must be obtained from the manufacturers of these machines.

ELECTRICITY IN THE RUBBER INDUSTRY

E. W. Pilgrim: Rubber as it is received by the manufacturer of rubber goods is in two forms, crude rubber and plantation rubber.

Crude rubber is gathered from wild rubber trees by natives and is worked up by them into balls about the same shape and half again as large as the American football, and before it can be used it must be washed to free it from dirt, after which it is worked up into sheets and dried.

Plantation rubber is gathered from cultivated trees, washed and dried at the plantation and shipped in the form of sheets.

The first treatment which crude rubber must undergo is washing. The large pieces of rubber are put in a tank of hot water and left to soak until softened. This makes it easy to free the rubber of dirt during the process that follows.

The large pieces, after having softened, are first put through a "cracker." This machine consists of two sets of rolls, both corrugated, and is really a rough washer. In this machine the rubber is torn up and rolled out into rough corrugated sheets. After passing through the cracker several times it is taken over to the finishing washer. This machine is the same as the cracker except that the rolls have finer corrugations. Here the rubber is rolled out into a fairly smooth sheet. Water is kept flowing over the material in both the above mills.

After washing the sheets are dried in a room heated by steam pipes or by hot air blown through by fans. A later process consists of putting the sheets in an oven heated by steam and from which the air is pumped, making a vacuum. Rubber is dried by this process very quickly.

The power required for driving the various machines in the rubber industry varies greatly as, for instance, a washer having two rolls, 16 in. diameter by 30 in. in length used in breaking down scrap rubber averages about 25 h.p., but if used for breaking down pure rubber gum the power required will be about 50 h.p.

The above figures are for individual motor drive. Most mills connect a line of washers to one motor, the motor being connected to a line shaft running beneath the floor. The washers being geared to this shaft, the peak load of one machine, which is often 100 per cent more than the normal load, will come during the light load of another machine and normal load is thus maintained on the larger motor. With this arrangement a 100-h.p. motor would be ample for five mills washing scrap rubber and a 150-h.p. motor for four mills washing pure gum rubber.

In a washing room having a rough washer containing three rolls, each roll 15 in. diameter by 24 in. long, running at 21 rev. per min.; two finishing washers containing two rolls, each roll 18 in. in diameter by 36 in. long, running at 25 rev. per min., and one tub heater, a 100-h.p. motor is installed and the following data are taken from a test record, breaking down crude rubber.

During this test the rough rolls were working, and the smooth rolls running light, the smooth having been loosened slightly.

Average line shaft speed	126 rev. per min.
Average speed of roll	21 rev. per min.
Average armature voltage	255
Length of record	11 min. 42 sec.
Minimum b. h. p.	3.45
Maximum b. h. p.	97.3
R. m. s. value of h.p.	33.1
Average value of h.p.	26.7

The above consists of both working cycles and periods of running light, while attendant was obtaining raw material.

The following are the values for any working cycle:

Highest average h.p. for any working period	53.5
Highest r. m. s. value of h.p. for any working period	54.5
Highest maximum horse power for any working period	97.3

These last figures represent the extent to which the rolls might be loaded provided the operator was kept continuously supplied with raw material, and should be used in case an individual motor is desired to operate each set of rolls.

The following figures cover similar conditions, rough rolls running light and finishing rolls under load.

Average speed of line shaft	126 rev. per min.
Average speed of rolls	25 rev. per min.
Duration of record	22 min. 10 sec.
Maximum b. h. p.	49.1
Minimum b. h. p.	5.5
R. m. s. value of b. h. p.	23.4
Average value of b. h. p.	20.8
Highest average b. h. p. any working period	41.5
Maximum h.p. for any working period	49.1

From the above we can assume that if both sets of washing rolls are to be operated continuously under load and driven by one motor, the motor should have a continuous capacity of 96 h.p. and be capable of a momentary overload of 143.4 h.p.

The peak loads come at a time when the operator throws large pieces of pure para rubber into the cracker. The momentary h.p. is very great but this drops off immediately after the stock is broken down.

Mill Line: The most general arrangement of mixing and warming mills is to connect a large motor to one end of a long shaft running underneath the floor and gearing the mills to this shaft. If there are only two or three mills connected a bar wound induction motor is satisfactory provided the power companies do not object to the starting load in which case motor with resistance in the rotor should be selected. Where there are a large number of mills connected a wound-rotor motor with external resistance must be used.

The mill line is always protected by a mechanical or electrical brake which can be applied in case of accident, from any machine.

In the mixing mills the rubber after it has been washed and dried is mixed with compounds which are thoroughly worked in. After this operation the rubber is stored until needed and before being used is put through the warmer where it is heated and softened to a condition so that it can be used.

The following data are taken from the test of a 375-h.p. motor driving a mill line to which were geared the following machines:

2 mixing and warming mills having one roll 20 in. diameter and the other 22 in. in diameter, each 72 in. long. Speed of rolls 25½ rev. per min.

1 mixing and warming mill, having one roll 20 in. diameter and the other 18 in. in diameter, each 60 in. long. Speed of rolls 26½ rev. per min.

1 mill having two rolls, each roll 20 in. diameter by 48 in. long. Speed of rolls 22 rev. per min.

1 mill having two rolls, each 18 in. diameter by 36 in. long. Speed of rolls 34 rev. per min.

1 mill used as a masticator having two rolls each 18 in. diameter by 48 in. long, running at 24 rev. per min.

On a typical run mixing compounds having about 30 per cent para the following results were recorded:

Maximum h.p.	345
Average h.p.	220
R. m. s. h.p.	225

Calenders: The calender is used for three different purposes: skim coating, which consists of spreading rubber over the surface of cloth; frictioning, which consists of rubbing the rubber into the fabric so that the cloth is entirely filled with rubber compound; calendering or sheeting rubber, which consists in passing the stock through the rolls and taking it off in sheets of different widths and thicknesses depending upon what it is to be used for. In the process of skim coating the top roll is hot and runs at about two-thirds the speed of the middle and bottom rolls. The middle and bottom rolls are cool. Cloth is passed between the bottom and middle rolls.

In frictioning all three rolls are hot. The top and bottom rolls run at about three eighths the speed of the middle roll, the fabric to be frictioned running between the middle and bottom roll.

In calendering all three rolls run at the same speed. The top roll is warm, middle roll hot and bottom roll cool, and the rubber is taken off the bottom of the bottom roll.

Each of the above operations is performed most efficiently at different speeds and in order to obtain uniform quality of product it is necessary that the speed at which the rolls run during the various processes remain constant as variations in speed with variations in load gives an imperfect product. Because the d-c. motor can be designed for a wide range of speed and controlled so as to give a small increase in speed with each step of the controller as well as the advantage of dynamic braking in case of emergency, this motor is preferred for calender-drives, the usual speed range being from 300 to 900 rev. per min. or 235 to 950 rev. per min. We know of one or two installations where a-c. motors are used for driving calenders, but on account of the impossibility of obtaining a wide range of speed, the a-c. motor is practically limited to driving calenders where only one class of work is handled.

The power required in calendering varies approximately directly proportional to the speed, although this rule does not apply for the lower speed as the power required is slightly more than a straight line curve would show. Frictioning requires more power as it is performed at a higher speed. Skim coating is done at intermediate speeds and calendering at the lower speeds.

The ideal drive for calenders on which all classes of work are performed consists of a d-c. three to one or four to one adjustable speed motor controlled by an automatic contactor control, the operator manipulating the control from the push button station located on the calender housing. The field rheostat mounted on the side of the calender housing and graduated in yards per minute controls the speed. From the push button station it is possible to start, stop, reverse, or slow down the motor for threading in another roll of fabric.

The following sizes of motors are usually supplied for driving three-roll calenders used in automobile tire factories:

18 in. by 54 in.	35 h.p.
20 in. by 60 in.	50 h.p.
22 in. by 60 in.	75 h.p.
24 in. by 66 in.	90 h.p.

The horse power mentioned above is the power required when the calender is operated at maximum speed.

One of the largest three-roll calenders built has rolls 32 in. in diameter by 90 in. face and requires a 250-h.p. motor.

The following data were obtained on a calender when running rubber compound at a constant thickness of 20 mils and varying speed, width of sheet 36 in.

Motor rev. per min.	H.P.	Surface speed of roll, yd.
462	4.88	23.5
500	6.25	25.5
535	6.22	27.3
571	6.35	29.1
618	7.67	31.5
670	8.15	34.2
638	8.17	32.6
600	7.02	30.6
570	6.73	29.1
500	6.20	25.5
455	5.62	23.2

The above tests were taken on a 16 in. by 44 in. calender and the table indicates the increase of h.p. with increase of speed.

The following table indicates the results obtained from the same calender and the same compound running at the same speed and varying the thickness of the stock.

Thickness of stock in mils	H.P.	Ft. per min. of rolls
20	10.4	30.3
30	7.7	32.3
40	6.10	32.7
50	4.96	33.2
60	6.24	32.6
70	7.00	32.2
80	6.38	32.3
90	6.92	32.5
100	6.46	32.6

The above table leads us to believe that the power required at a given speed varies inversely as the thickness. The most important factor which has a considerable effect on the power consumption and one which causes varying results when different conditions are varied is the size of the rolls which are fed into the calender. It is evident that when a large roll of compound is being fed into the calender a large surface of the calender roll is rubbing on the compound and the power required to reduce large rolls of compound to sheets is consequently greater than that required for the smaller rolls.

The following is a list of typical installations:

Size of mill	H.P.	rev. per min.	Material
22 by 60 in. warming....	75	720	automobile tires
10 by 22 by 36 in. rubber refiner.........	40	720	" "
18 by 36 in. three-roll washer..............	75	900	" "
16 by 24 in. sheeter......	20	720	" "
18 by 40 in. warming....	40	720	" "
24 by 66 in. three-roll calender............	90	300/900	" "
Tube machine..........	15	900	" inner tube

One tube wrapper, one buffing machine and one rag wrapper for automobile inner tubes, 5 h.p.—1800 rev. per min. belted to line shaft.

One 100 h.p. 600 rev. per min. motor driving one 16 in. by 24 in. washer, one 14 in. by 30 in. tin roll, one 14 in. by 34 in. tin roll, one 14 in. by 18 in. by 28 in. dust grinder, one wash tub, material manufactured hard rubber novelties.

One 200 h.p. 600 rev. per min. motor driving three 18 in. by 50 in. and one 50 in. by 36 in. warming and mixing mills, material manufactured hard rubber novelties.

One 75 h.p. 720 rev. per min. motor for driving one 16 in. by 42 in. mixing mill, one 15 in. by 24 in. washer, one tube machine. Material manufactured, automobile inner tubes.

The usual arrangement of the factory for the manufacture of automobile tires is as follows:

At the rear of the building are the washers, drying room, and compounding rooms. Along each side and near the windows are the calenders. Between the two rows of calenders are the mixing and warming mills. Cloth drying machines are installed convenient to the calender. Next along one side of the building are the fabric cutters and then the tire wrapping machines. On the opposite side are the vulcanizers. The offices and storeroom are near the front of the building.

L. L. Tatum: There is one point that has been standing out before me very strongly for the last year or so, and that is as to the increased responsibility for the completeness of the equipment on the part of those in the electric art who are making industrial motor applications. The papers this afternoon have brought out a thorough study of the power applications, the type of motor required, and the conditions under which the motor is operated. Machinery people treat that as a foreign art. Due regard to economy requires that most of our applications should be made on new machines, and that means the manufacture of new machinery rather than the rebuilding of existing machinery.

To too great an extent we have considered our responsibility as ended when we recommended suitable equipment. We have not carried our responsibility further to the proper assembly of the equipment on the machine. Many of these machines go into small plants that maintain no suitable electrical force and are at the mercy of the local contractor for assembly and installation, and my own experience has been that the machines suffer a good deal from these local contractors. That fact was driven home particularly one Sunday afternoon this past winter when I was called out to help a poor fellow get his machine running by Monday morning. He could not find any one else. The local contractor had fallen down completely. It was a simple job, but before the owner of that plant gets through with it, there will be trouble. The plant will be condemned by the wiring inspector, and condemned by the safety man. They had on the machine so-called safety features which no safety board would pass.

The responsibility of the man who provides the motor, in my opinion, should include the complete installation, to see that it is properly mounted, adjusted, and connected, so as to relieve the man who buys the installation from the constant annoyance of condemnation by inspectors of his apparatus, and the expense of rebuilding it before he gets it right.

There are one or two machinery manufacturers who carry their assembly to the complete mounting of the motor and controller, wiring them complete, ready for the attachment of the power wires, which any ordinary contractor can do in proper form. This practise should be the rule, not the exception.

I find that a great many possible users of electrical machinery are afraid to put it in, just because of the trouble they always get into through improper assembly and installation. The responsibility should rest on the machinery man of making the equipment complete. This is a matter of education of the machinery manufacturer which we are in the best position to carry out.

J. C. Lincoln: There was one installation made in a printing plant in Cleveland which may be of interest, in showing how some problems are met. The manager of this particular plant was an "efficiency man". He wanted to find out how the workmen were doing. He knew that some of his job pressmen would start out, and when he was in the room would run the presses so as to get 2,000 or 2,100 impressions an hour, and when he was not in the room they would not get out so many. This installation was put in, and information was given the manager of the plant of the operations of the men in this way: He had some twelve or fourteen small job presses and about eight or ten large presses, varying in size, the presses requiring a motor of from 5 h.p. to 15 h.p. On a large board in his office was placed a voltmeter, and then a meter and lamp for each press in the establishment. Connections were made so that whenever the press was running the lamp belonging to that particular press was lighted. Furthermore, these voltmeters were so calibrated that the impressions per hour were given by the meter. In this way the manager sitting at his desk could look at the switchboard and see at a glance which presses were in operation and how many impressions an hour they were producing. The plan has been in operation for two or three years. We have not heard any complaint about it, and presume it is giving good service.

J. H. Davis: I was very much interested in Mr. Stafford's paper on electricity in grain elevators because the matter of the exportation of grain is of unusual importance on account of the European war. We have two very large elevators which we are about to electrify, and the question of just how to do it is under consideration and has been for some time.

I have not had an opportunity of reading Mr. Stafford's paper very critically, but in looking over it superficially I see no reference to the vacuum system of handling grain. From my viewpoint, it would appear that that system of handling grain offers many advantages over the old method.

I think perhaps it may not be out of place to mention here some of the difficulties in the way of the present method of handling grain. I presume Mr. Stafford has studied the subject very closely, perhaps much more closely than I have, but it falls to my lot to decide how we shall do these things, so far as our own elevators are concerned. When the cars come to us loaded, we will say with wheat, they have an additional door known as a grain door, made of rough timber and nailed to the car, inside of the regular door, which is closed, and the car is sealed. The cars reach us and we take them in eight- or ten-car lengths into our grain elevator and there we have track pits and the regular door is opened and the grain door is taken down. It is quite a problem, to remove these grain doors. Unless you have actually seen the difficulties involved, you do not appreciate how it delays or slows down the whole operation. What I am getting at is this—by the vacuum system of handling grain we can allow the grain door to stay as it is by simply carrying into the car a reinforced hose, built around a wire frame so as to prevent collapse of the hose, as the air is removed. This method would readily provide for the removal of the grain, would not necessitate the removal of the grain doors and it would entirely remove all necessity for shoveling the grain through the doors of the cars. It may be that such a method of handling grain will not prove to be practicable. A test has recently been made at Quebec of this method of handling grain, but unfortunately I was unable to have a representative there, but I understand that, while they were in a measure successful, the details of the equipment were not worked out so as to be entirely successful in every respect.

DREDGES AND EXCAVATING MACHINERY

H. W. Rogers: Mr. Rushmore presents a table of manufacturers by industries in which are mentioned, "Iron and Steel" and "Copper, Smelting and Refining". Both of these industries naturally suggest the mining industry on which they are dependent and with which they are closely allied. Under the heading of "Costs", Item 4, reference is made to the economic value of electric drive, which introduces the subject of the electrification of dredges and excavating machinery.

In so far as the mining industry is concerned this type of machinery may be classed under the following heads:

1. Dragline excavators.
2. Revolving shovels.
3. Railway shovels.
4. Strippers.
5. Hydraulic dredges.
6. Elevator dredges.

The dragline excavator or bucket-scraper has a limited field of operation in the California gold fields but otherwise is confined almost entirely to contracting work, while the revolving shovel, railway shovel, and stripper are used very extensively in mining operations, particularly in the iron and copper mines of Michigan and Minnesota, the copper mines of Utah and the coal fields of Kansas, Missouri and Virginia.

The dragline excavator might be classed with the locomotive crane and revolving derrick as it is of similar construction, and, since such machines operate on a very much slower cycle than the shovel, which is equipped with a rigid dipper handle, they may readily be equipped with either d-c. or a-c. motors depending on the source of power available. In the electrification of a shovel there are many important points to be considered and what may be said of the railway shovel is equally true of the revolving shovel and stripper, the latter being really a revolving shovel of a much larger type and greater capacity.

There is probably no other class of machinery that presents a duty cycle as severe as that of the shovel, which is very short, varying from 7 to 12 sec. on the hoist, from 7 to 12 sec. on the thrust, and from 10 to 18 sec. on the swing, making a complete cycle in from 17 to 30 sec. and the motor to meet these requirements must have a sufficiently low armature inertia to permit of rapid acceleration and quick reversals under small power. It should also be a motor of rugged design as it must be subjected to severe overloads and shocks and frequent reversals. This is especially true of the hoist motors, and, to a lesser degree, of the swing motor; the thrust motor being practically stalled during the digging operation, although it may revolve or overhaul, according to conditions, and is operated at full speed only after the hoisting operation is completed.

In laying out an electric shovel drive there are really four things to be considered; namely, the speed at maximum torque, the speed at light load, the power required by the motor, and the gear ratio. An increase in the gear ratio results in a decrease in power at both light and heavy loads, and increase in the speed at heavy loads, and a decrease in the speed at light loads.

The d-c. series motor has the characteristics of the steam engine, in that it gives its heaviest torque on starting, speeds up under light loads, and slows down under heavy loads. It is much easier to control and requires considerably less apparatus, in so far as the control is concerned, than the a-c. equipment.

With the a-c. slip-ring motor it is impossible to obtain the maximum torque on starting; and the light-load speed, which is very important, is limited by the synchronous speed. The only means of improving this disadvantage is to reduce the gear ratio or use a higher speed motor, either of which methods would mean an increase in the capacity of the motors and an increase in the inertia, which would result in an increase in the power required and a slower acceleration, both of which are undesirable. Under such conditions the natural result is a much larger kv-a. capacity in transformers for the induction motors than the kw. capacity of motor generator set for the d-c. motors.

There is undoubtedly a greater demand for electric shovels for a-c. operation than for d-c. operation, but neither type of motor should be applied without a full knowledge of the existing conditions and the characteristics of the steam engine, as misapplications will only tend to defer progress in this field of engineering. A very careful study of this subject in connection with existing electric shovels and thorough testing has proven beyond all doubt that the d-c. series motor is better adapted to this service than the a-c. slip-ring motor, and, although it is possible to operate a shovel with slip-ring motors the disadvantage of such an application render it undesirable.

It can be safely said, however, that with a proper application of motors, the electric shovel will equal or surpass the steam shovel in every respect and will eventually replace it. Although the electric shovel requires an increased investment, the reduction in labor and repair charges and the elimination of boiler and feed water troubles will warrant it.

The saving in operating expense of the electric shovel over the steam shovel will depend somewhat upon the comparative cost of coal and electric power and will vary for different localities, but it should be remembered that the electrically operated shovel eliminates the fireman, the watchman, the coal passer, teaming of one-half day, the use of water, and considerable waste. The natural increased wear and tear of parts having a transverse motion as compared with those having rotary motion should be considered.

The following data applies to one of the larger types of shovel, but is typical of all shovels and clearly indicates what may be reasonably expected of the electric shovel. In these figures no account whatever has been taken of the possible saving in the cost of fuel as this must be considered for each individual case.

Labor per Shift.	Steam	Electric
Shovel runner	$ 6.00	$ 6.00
Craneman	4.00	4.00
Fireman	2.50	....
Six pitmen at $1.75	10.50	10.50
One watchman	1.75	....
One coal passer	1.50	....
Teaming (½ day)	2.50	....
Oil and waste	1.50	.75
Total	$30.25	$21.25
Saving, electric over steam	21.25	
	$ 9.00 per shift.	

For convenience in comparing the costs of operation on steam and electric shovels the costs are all reduced to a day basis.

		Electric	
			Equivalent
	Steam	d-c.	a-c.
Interest at 6 per cent	$ 5.20	$7.75	$10.85
Depreciation at 4⅔%	4.03	6.00	8.43
Repairs at 10%	8.66	....	....
Repairs at 6%	....	7.75	10.85
Labor per shift	30.25	21.25	21.25
Total cost per shift	$48.14	$42.75	$51.38

It has been assumed that, owing to weather conditions, delays, etc., the shovel working year consists of 150 days, and the above figures are based on this assumption; also that the shovel is only working one shift a day.

If the shovel works three shifts a day instead of one shift a day, the interest and depreciation will remain the same, provided the shovel is kept in repair. It is reasonable to assume that the repairs will increase when working three shifts, but not in direct proportion; therefore, this item has been increased 50 per cent.

		Electric	
	Steam	d-c.	Equivalent a-c.
Interest at 6 per cent	$5.20	$7.75	$10.85
Depreciation at 4⅔%	4.03	6.00	8.43
Repairs at 15%	13.00	....	....
Repairs at 9%	....	11.63	16.28
Labor (three shifts)	90.75	63.75	63.75
Total cost (three shifts)	$112.98	$89.13	$99.31

These figures clearly indicate that the electric shovel is a better proposition than the steam shovel, that the d-c. equipment is far superior to the a-c. equipment and that the saving in operating expenses will warrant the increased investment.

The control on either the d-c. or the a-c. equipment is reversible and entirely automatic, all panels being equipped with automatic acceleration, the hoist and crowd panels being also equipped with a "jam" relay which inserts resistance in the circuit in case of very heavy overloads but does not open the circuit, the resistance being automatically cut out again by the same relay when the overload disappears. The master controllers are located similar to the operating levers on a steam shovel so that a steam operator will be entirely at home on an electric shovel.

In selecting a shovel equipment it should be remembered that although it is possible to operate with alternating current, it is cheaper to use the d-c. equipment, even with a motor-generator set, and have an outfit which more nearly approaches the characteristics of the steam shovel, and has much simpler control apparatus and requires considerably less power to operate it than the a-c. equipment with transformers.

The hydraulic or suction dredge has never been favorably considered for mining operations although the modern elevator dredge followed closely and was, in a large part, due to an attempt to mine with the aid of powerful pumps which were suggestive of a more highly satisfactory method. It has long been used, however, as a successful machine, by contractors for excavation of material below the water level and, although not designed for the excavation of rock, such material frequently passes through the pump without any difficulty. Ordinarily it is used in sand, gravel or loam, although there is one at Columbus, Ohio, working in blue clay and one at Calumet working in copper tailings.

The electrical equipment of such machines is not entirely new as there are quite a number that have been in successful operation for several years.

The greater portion of them, however, are steam operated. Ordinarily the equipment consists of the main pump motor, the cutter motor, the winch motor, the service pump motors and bilge pumps, with the necessary control and switchboard but these may be and often are supplemented by a compressor motor, a small motor-generator set for the searchlight or an additional motor for operating a "giant." The operation of such machines is practically continuous and it is an ideal application for a-c. induction motors. The main pump, which is by far the greater portion of the load, may vary between 200 h.p. and 1250 h.p., depending on the size of pump and the head against which it operates. Since the greater part of the head is friction head and the discharge line varies in length between wide limits it is necessary to compensate for this change in the speed of the pump and consequently a variable speed induction motor should be used with provision for from 25 to 33 per cent reduction in speed.

Both the cutter and winch motors should be of the variable speed type while the remaining motors may be squirrel cage type. While there may or may not be a saving in the cost of power, there is a saving in labor and repairs and a considerable saving in the first cost of the dredge resulting from the use of motors.

The hull may be smaller and the operating hours longer, while the dirt and grease resulting from the use of boilers, steam engines and coal bunkers is eliminated.

The elevator dredge of the close connected bucket type is used to a certain extent for excavation but is largely confined to gold and platinum mining. It varies in capacity from 3½ cu. ft. buckets to 16 cu. ft. buckets and consists essentially of a digger or bucket line; revolving screen, sluice tables and boxes, stacker for carrying away the tailings, high and low pressure pumps, priming pumps, amalgamator and occasionally a sand pump and "giant." There are more than a hundred of these dredges operating in the country and although some are equipped with steam engines, the greater part are electrically driven with a-c. motors.

The steam driven dredge can hardly be considered economical in sizes larger than 7½ cu. ft. and it is practically impossible to operate the largest ones with steam as there is no available space for such an equipment, in fact, the larger sizes of dredge practically owe their existence to the electric motor.

THE SUGAR INDUSTRY

C. A. Kelsey: Few people realize the extent of the sugar industry. Sugar is commonly considered as a luxury but although a large part of the total production of sugar is used in the manufacture of confections there is still a very considerable amount used directly as a food product.

The total world production of cane and beet sugar for the season of 1913-1914 was 18,687,000 tons, of which 9,777,000 tons was cane sugar. The United States imported in the year 1913, 2,890,667 tons but produced only 852,472 tons, making a total consumption of 3,743,139 tons. This gives a per capita consumption of 85.4 lb. per annum. Of the above amount consumed in the United States, cane sugar constitutes the greater portion, the amount of beet sugar being a very small portion of the total.

Briefly the process of producing sugar from cane consists of expressing the juice from the cane, evaporating the water, crystallizing the sucrose, and separating the sugar from the molasses.

The cane is delivered to the mill on special flat cars having the sides and ends of open construction. There are two ways of delivering the cane from the cars to the cane hopper. First, by transfer hoist, whereby portions of a carload are lifted out of the top of the car by cables which have been passed around the cane. This requires a hoist motor mounted on a standard hoist. Second, the car is switched on to a track section which can be tilted either sidewise or endwise. In the former case, the platform can be tilted around a balanced point requiring therefore a very small motor of intermittent rating. Where the car is tilted endwise, a hoist motor mounted on a standard will generally be employed. This requires a motor and hoist of sufficient capacity to lift half of the combined weight of the car and cane.

The cane is dumped in to a hopper from whence a conveyer pulls the cane up on to the main cane carrier. The idea of breaking the conveyor up into two sections is to provide means for depositing a uniform layer of cane on to the section feeding the crusher. Both sections of the cane conveyor require variable speed drive. The second section or main carrier requires variable speed in order to give a constant feed to the crusher, depending upon the character of the cane and the desired rate of grinding.

The crusher consists of a set of two corrugated rolls and is intended to break up the cane into short sections and to lay it open so that the main rolls can force out the remaining juice. The main rolls are adjusted to deliver a constant thickness of crushed cane to the succeeding rolls. As the crusher extracts about 65 per cent of the total juice, the portion going to the first mill is composed largely of fiber. With a variation in the percentage of fibre content in the cane coming from different sections or at different periods of the season, the amount of crushed cane delivered by the crusher with a constant feed, will vary. As the rolls require with a given speed a constant rate of crushed cane the crusher must operate at variable speed.

An operator is required at the crusher to regulate the feeding of the first roll and as alternating current is best suited for the general mill conditions, a variable speed motor of the wound-rotor type is satisfactory for the service.

As mentioned before, the main rolls are adjusted for a constant spacing between the rolls. A variation in the character of the cane producing a higher or lower percentage of fiber or a variation in the rate of grinding, calls for both a difference in the relative and absolute speeds of the different rolls. The relative speeds can be obtained by suitable gearing to motors of the same speed where the mills are to be individually driven. These speed ratios are, however, suitable for one class of cane. With a varying cane it is desirable to readjust the relative speed. Variable speed motors have not proven satisfactory under these conditions as the load is found to vary from time to time even when care is taken to produce a uniform feed. The variable speed a-c. motor under these conditions gives an unsatisfactory speed regulation, rendering it difficult of control.

There are times when on account of shortage of cane or some reduction in the capacity of the sugar house, that it is desirable to keep the rolls running at reduced output. As mentioned before the speed control of a variable speed motor, driving cane rolls is unsatisfactory. A means of meeting this requirement, is however, had, in reducing the frequency and voltage of the a-c. circuit, by means of the reduction in speed of the prime mover. Where the pumps have been designed to meet this condition, the frequency of the whole power system can be reduced, as all of the pumping and conveying apparatus can properly be correspondingly reduced in speed. One exception to this is the centrifugals, which must be operated at their proper speed in order to insure completely drying the sugar crystals. This can be taken care of, however, by splitting up the power circuits leaving the main rolls to be driven by an independent generator. The motors for the main rolls should therefore be constant speed type, but on account of their size, and the high static friction, which they have to overcome, they should be of the wound rotor type with a resistance for starting purposes only.

The crushed cane coming from the last set of rolls is called bagasse, and is conveyed by scraper type of conveyers to the furnaces, usually located between the boilers. In a properly electrified sugar mill the bagasse should meet all of the requirements for fuel with the exception of a very small amount of wood required to kindle the bagasse. These conveyers operate at constant speed and as the material is soft and not liable to jam the conveyer, constant-speed squirrel cage motors are here employed.

The juice extracted by the crushing plant is delivered to a screen where particles of cane are filtered and left on the screen. A scraper conveyer takes the cane refuse from the screen and deposits it on a cross conveyer, which in turn dumps it on to the cane passing between the first and second set of main rolls.

The raw juice is pumped to alkalizing tanks where milk of lime is added. This is to neutralize the acids formed by fermentation and to produce insoluble compounds from the non-sugar element. Centrifugal pumps are here employed, driven by constant-speed squirrel cage motors.

The milk of lime is produced in the plant by the solution of slaked lime, the action taking place in a small tank provided with a paddle for stirring up and mixing the contents. From here it is pumped to a storage tank. A small centrifugal pump is here used to discharge the mixture. The motor is a constant speed, squirrel cage type.

The tanks into which the raw juice is discharged and in which the milk of lime is added, are provided with some means of mechanically mixing the milk of lime and the raw juice. The paddles are either driven direct by vertical motors or geared down to horizontal motors, in either case constant speed squirrel cage motors are used.

The alkalized juice is then pumped through a heater from whence it discharges into defecator tanks. Here the juice is brought up to the boiling point in open tanks. The heat acting on the albumenoids forms a flocculent precipitate. Part of this settles to the bottom and part rises to the surface, forming a thick, black dirty scum. The clear liquid forms in between two layers and is then decanted and pumped to the evaporators or multiple effects. A centrifugal pump is here used driven by a constant speed squirrel cage motor. The scum and sediment are diluted with additional water and then passed to the filter presses. The nature of the material requires a triplex pump. The pump is driven by a constant speed squirrel cage motor. The size of the motor permits its being thrown on to the line in case a compensator does not give high enough starting torque. The filtered juice follows the path of the defecated juice while the filter cake is dropped down from the filter presses to a conveyor which carries the cake to a car whence it is transported to the field and used for fertilizer.

The defecated juice flows through the multiple effects where it is evaporated down to a consistency of syrup. Evaporation takes place under successive stages of vacuum and correspondingly lower temperatures. The syrup is either pumped to storage tanks near the vacuum pans or flows by gravity. Centrifugal pumps are here used driven by constant speed, squirrel cage motors. The condensed vapors from the juice in the multiple effects are drawn off from the different vessels and are either pumped to a tank for use as maceration water at the rolls or discharged to the hot well. Centrifugal pumps are here used driven by constant speed squirrel cage motors. The syrup is drawn up into the vacuum pans where it is boiled to grain. The first sugars, that is those sugars coming from the original boiling of the syrup, are let out of the pans directly into a tank over the sugar centrifugals. Here the sugar and molasses called massecuite is fed into centrifugal machines. The centrifugal machine is practically the only machine in the sugar mill requiring a specially designed motor. This refers to the direct coupled motor. The centrifugal is first loaded with a charge of massecuite. It is brought up to speed, requiring a high accelerating torque. It is allowed to run for a minute or two, depending upon the grade of the sugar, and is then brought to rest by a brake. The molasses is thrown out by centrifugal force through the wire gauze lining of the centrifugal and the sugar crystals are left in a thick layer on the inside surface of the centrifugals. After dumping out the sugar by mechanical scoops or by hand, the centrifugal is again loaded and the process repeated. The direct coupled motor must be designed to accelerate the centrifugal quickly and bring it up to a predetermined speed. It is usually operated a short time at top speed so that the ventilation is limited and a fairly large motor must be utilized, in comparison to the accelerating and running torques.

The molasses is mixed with the syrup coming from the multiple effects in an attempt to crystallize more of its sucrose contents. Usually the massecuite produced in this manner is discharged from the pans into crystallizer tanks. These tanks are provided with paddles intended to keep the contents in slow motion. The sugar crystals are thereby brought into contact with the non-crystallized sucrose and grow larger. These crystallizers are driven by constant speed squirrel cage motors.

The sugar discharge from the centrifugals drops into either a screw or vibrator conveyer and discharges into a bucket conveyer leading to a bin from whence the sugar is discharged into bags for shipment. These conveyors are usually driven from the main centrifugal shaft where group-driven centrifugals are employed, or can be driven by individual motors of the constant speed squirrel cage type.

Where the centrifugals are belted they are grouped and shaft sections are driven by constant speed squirrel cage motors.

The circulating water for the condensers is pumped by centrifugal pumps, driven by constant speed motors. These motors may be squirrel cage type or wound-rotor type with starting resistance depending upon their size as compared with the power system.

The molasses from the centrifugals is pumped to the storage tanks serving the vacuum pans or to the outside storage tanks by triplex pumps. Constant speed squirrel cage motors are suitable for this service. The vacuum pumps and air compressors when used can be satisfactorily operated by constant speed induction motors, either of the squirrel cage or wound-rotor type, depending upon the size of the motors in relation to the power system.

The blowers for the boilers are best driven by variable speed motors, to provide a means for varying the furnace draft. Wound rotor motors are suitable for this service.

The boiler feed pumps should be capable of delivering a variable amount of water to the boilers. This can be accomplished by driving them by variable speed motors or the discharge of the pump can be throttled.

There are miscellaneous applications around a sugar-mill factory, such as driving service water pumps, laundry tubs for the filter bags, the carpenter and machine shops, but these applications are simple and not peculiar to the sugar industry.

In general, it may be said that the application of motors to cane sugar mill apparatus consists in a detailed study of the particular apparatus to apply standard motors. The pressure heads and quantities of the various liquids to be pumped are determined by the layout of the mill and these data must be collected at the mill and the proper pumps and motors selected. The same applies to the conveyers, blowers and miscellaneous belted and direct-coupled apparatus.

THE PAPER MILL INDUSTRY

W. L. Merrill: Experience has shown that with the exception of driving the variable speed end of paper machines themselves, the a-c. motor offers a great many more advantages than the d-c. motor and at the present time is being generally used throughout the industry.

For convenience in the following table the motors have been divided into four types designated: A—Squirrel Cage Motors, B—Internal Resistance Motors, C—Collector Ring Type of Motor, D—Synchronous Motors.

A—Squirrel Cage Type of Motors: The squirrel cage type of motor is essentially a constant speed motor and the speed can not be appreciably changed, has high starting torque, high efficiency, and high power factor. In the larger sizes it is customary to use compensators for reducing the voltage applied to the motor at the time of starting. This is not to protect the motor, but to avoid heavy fluctuations on the line. It will, therefore, be seen that squirrel cage motors should not be used; first, where speed reductions are required; second, where at the time of starting it is desired to start slowly or to "jog" the load; third, where sudden shocks are objectionable at the time of starting, such as in the chain drive on beaters. In group drives where belts are used, these shocks are absorbed partially, by the belts and are not objectionable.

B—Internal Resistance Motors: The internal resistance motor has high starting torque, high efficiency, and high power-factor, similar to the squirrel cage and has the advantage of being able to gradually increase the speed of the motor until the machinery comes up to speed and is satisfactory for service where the load has small inertia, or is practically all friction and the time of acceleration does not exceed about one minute. The internal resistance, however, can not be made large enough to give any speed regulation and the motor must be treated as a constant speed machine. This motor is satisfactory for group drives of average service conditions, such as screen rooms, sulphite departments, etc.

C—Collector-Ring Type of Motor: The collector ring type of motor has a high torque, high power factor, and efficiency somewhat lower than the above two types. It may be either constant speed or varying speed. As a constant speed motor it should be used where heavy starting duty is required, since it is possible to proportion the external resistance used in connection with a drum controller to meet almost any condition of starting required. With liberal resistance grids, several successive starts can be made without injury to the motor or controlling appliances, such as breaking a wood conveyer loose when jammed with ice or for starting heaters after the stock has settled. A squirrel cage motor under similar conditions might injure the conveyor or jump the roll out of its bearings. As a varying speed motor it can be used where a certain amount of speed regulation is required provided it is not objectionable to have the speed change as the load changes; *e. g.*, cranes, hoists, etc. It is not applicable to drives where constant speed is desired at different loads with one setting of the controller. As the load decreases, the speed increases and vice versa.

D—Synchronous Motors: Synchronous motors have low starting torque as compared with the above types, high efficiency, and an adjustable power factor and can be often used advantageously for improving the power factor of the system. Before installing a synchronous motor, however, conditions of operation should be thoroughly studied, as many times the lower power factor is due to many motors on the system running at partial loads.

Synchronous motors should not be installed on line shafting or individual machines where a heavy starting torque is necessary, unless they are provided with clutches or some means of relieving the load at the time of starting. The starting torque, in general, is limited to about 30 per cent of full load running torque. The synchronous motor can be used to advantage to supply auxiliary power to a line shaft already driven by a waterwheel or an engine, power being obtained from another station.

The synchronous motor also has a field in the industry in connection with low pressure turbines. Where there are one or two reciprocating engines, it is often advantageous to install a low-pressure turbine and supply power to various motors throughout the mill; also to "pump back" on the engine or main line shafting with the synchronous motor. A combination of the engine or turbine and the synchronous motor is self-regulating.

Drives in General: It is undoubtedly needless to call attention to the desirability of having all transmitting parts, such as belts, rope drives, gears and chains of ample proportion throughout the mill. Large motors which are to run continuously on heavy work with belting under severe conditions should be equipped with three bearings; two-bearing motors under these conditions have in many cases proved successful, yet the occasional renewal of the bearing linings more than warrants the added expense of the three-bearing installation.

ELECTRIC DRIVE IN PULP AND PAPER MILLS

TYPES OF MOTORS: A—Squirrel Cage; B—Internal Resistance; C—Collector Ring; D—Synchronous

Machine	Type of motor for individual drive.	Connections	Remarks.
Grinder lines	C or D	Direct-connected through flexible coupling or solid.	In case of single stone a higher speed motor may be used with rope drive.
Flat bed screens			Groups of several lines use B or C or D. Individual line use A with gear or chain.
Rotary screens			Little power required—can be arranged for individual drive.
Centrifugal screens	A	Belt to pulley on top or pulley on bevel gear shaft.	Can be arranged for direct connection to vertical motor or to horizontal motor through the bevel gear.
Silver screens	A	Belt or gear.	When group driven they are usually connected to a main group of machines.
Circular saws	A, B or C.	Belt direct-connected through flexible couplings.	
Band saws	C with enclosed collector rings		
Small conveyers	C	One belt in the reduction (for mechanical protection).	Belt can slip in case of clogging. Starting resistance should be liberal for slow starting and breaking loose.
Heavy conveyers and log hauls	C	Same as for small conveyers.	Same as for small conveyers.
Chippers	C	Belt.	A combination design is feasible for direct connection.
Barkers	A	Direct-connected.	
Jordans, Marshalls and Clafins	A, B, C or D	Direct-connected through flexible coupling-sliding motor or telescoping coupling.	New type Marshall has adjustable shell. Drive through solid coupling or flexible coupling.
Beaters and washers	C	Chain or belt.	Usually driven in pairs from one motor. Chain should be amply large. With belt drive motor may be in basement. Liberal starting resistance needed in any case.
Wet machines	C	Gear.	C used to give slow speed for adjusting felt.
Deckers		Belt.	Group drive by A or B on account of low power and speed.
Super calenders	Direct current special or a-c. small motor A, large motor.	Gear. Gear and clutch.	D-c. motor has field and shunted armature. Group drive usual on account of uniform speed. Individual drive has operating advantages.
Sheet calenders	C	Gear.	
Platers	A		Combination individual drive now available.
Pumps	A or B	Solid coupling direct-connected	
Agitators	A or B	Belts and gears.	Slow speed and small power. Usually driven from some other group of machines.
Shredders	A or C	Belted or direct-connected.	A or C motors according to size. A motors should have high torque rotors C motors with ample starting resistance.
Rag cutters, dusters and threshers	A	Belt or gear.	A motor is preferable for individual or group drive where power conditions permit, on account of amount of dust.
Rotary boilers	A	Gears.	
Rotary furnaces	A	Gears or gears and belt.	
Rotary cutters	A with mechanical speed change or adjustable d.c.		Many of these machines can be purchased equipped with motors.
Vertical cutters	A	Gear or belt.	Many types on market ready equipped with motors

Silent Chains: Silent chain drives, particularly, should be chosen of liberal size for the work they are to do. This is true of beaters, where continued sudden shocks are apt to come on the chain.

THE PORTLAND CEMENT INDUSTRY

C. C. Batchelder: The Portland cement industry affords a good illustration of the application of electrical apparatus on a large scale where a careful selection of the equipment and attention to comparatively inexpensive protective measures have a great bearing on the service obtained. Cement making is primarily a grinding process and involves reducing the material to a fine powder twice in the course of its manufacture, once before and once after burning. This means a large specific power consumption. Each barrel of cement requires about 20 h.p-hr. in the course of its manufacture, and as the average production of American cement plants is over 2000 barrels a day the aggregate power used by the industry is enormous. Cement manufacturers are vitally interested in power production and distribution. It makes up a very appreciable portion of the cost of their product and must therefore be economical. Its supply must be continuous and reliable, and at the same time capable of adjusting itself to a demand that varies with the seasons.

Cement mills have a few characteristics which differentiate them from most other manufacturing plants.

The principal difficulty with which motors and control appliances have to contend in cement plants is the large amount of abrasive dust in the air. While an increasing amount of attention is being given to dust elimination and collection, there are very few plants in which the air in the rooms containing the crushing and grinding machinery is clean enough to allow motors with unprotected bearings or collectors to operate without requiring an abnormal amount of attention. The engineer must meet this condition by putting the electrical apparatus in separate motor rooms whenever practicable, by specifying bearings protected from dust by shaft dust washers and tightly seated oil well covers, and by selecting low-speed motors. Ordinary gearing should be avoided, and if used at all, should be protected by tight cases. It is a good plan to have compressed air piped throughout the plant so that the motors can be blown out at regular intervals. Control appliances should be of as simple a nature as possible, and if relays are used they should be enclosed by dust tight covers, or installed in cabinets if they must be placed in dusty parts of the plant.

Crushing and pulverizing machinery is usually rather roughly built and to prevent excessive vibration and shock being transmitted from the machines to the driving motors, requires that the mechanical details of a motor installation be laid out in a conservative manner. Motor foundations should be rigid; flexible couplings should be used between direct-connected units; and bearing pressures and rubbing speeds should be kept low.

Much of the cement-making machinery requires somewhat more than normal running torque at the instant of starting, and the motors must be capable of exerting this torque if trouble is to be averted. This does not affect the design of d-c. and slip ring induction motors, but as the greater part of cement machinery is driven by squirrel cage motors it is usually necessary to bear this starting torque requirement in mind when selecting the electrical equipment. As a matter of fact a change in the motor design to secure higher torque is very seldom necessary, and standard machines can take care of the great majority of drives satisfactorily. This has been especially true since the introduction of practically indestructible rotor construction.

High room temperature is a factor that sometimes affects the motor equipment of the kilns, and dryers, and various expedients have been adopted to protect the motors driving this machinery when the conditions were such as to require special precautions, such as placing the motors in ventilated tunnels, or in spearate rooms.

While the general tendency of industrial engineers is toward the adoption of individual drive, there are a few cases in cement plants where a well worked out group drive will give better results. This is particularly true of small elevators and conveyers, which are often subject to rather violent load fluctuations, so that individual motors must be of considerably larger capacity than required by the average load of machine, while if grouped, the driving motor can be safely worked at practically full capacity.

Careful attention to the features in which cement mill service is especially severe will make an electrical installation almost as free from trouble as in more favorable industries, while neglect of the proper precautions in laying out a motor equipment may cause a large expense either in the form of maintenance charges or the cost of changes after the equipment is installed.

THE HANDLING OF FREIGHT IN TERMINALS

R. H. Rogers: As recorded in Mr. Rushmore's paper, "The valuation . . . . . . of electric motor application . . . is so special as to necessitate its separate statement for each industry."

This sentence paves the way for an exposition of the advantages of electric motors in an industry closely interwoven with every kind of manufacturing, namely: the handling of freight in terminals—the Siamese twin with transportation.

The movements of raw materials, of processed materials, of manufactured and assembled products and food stuffs on their halting way to consumer and the subsequent return of scrapped material, waste and by-products to the grand circuit necessitate a continuous high-pressure system of freight handling at every twist and turn, at the beginning and end of every transition from one classification to another and in every community.

Until recent years this great labor has been performed by hand and the first part to be mastered by power was the handling of bulk materials. Package freight handling has only recently been invaded by mechanical methods involving machines and motors.

Steam power and hydraulic and pneumatic methods have been introduced and are still maintained to some extent but the really successful agent and the thing that has done most to mechanize this work is electricity through its field piece—the motor. Motor-operated machines for the handling of bulk freight are:

Various forms of derricks operated by multiple drum and often multiple motor winches.

A multitude of machines under the general title of cranes with one, two, three or four motions with corresponding motors.

Gigantic machines and combinations of machines for specialized work in great quantities, as typified by ore and coal bridges, ore and coal dock equipments and car dumpers using motors in great variety of sizes and characteristics with corresponding highly developed control apparatus.

Continuous conveyers for free-flowing bulk material, used for elevating, horizontal and lowering movements between cars, ships, storage piles or warehouses and elevators; equipped with motors section by section with self-protecting control devices.

Complicated engineering problems are involved in the design and selection of motors and control to secure the greatest possible speed in the motions and the greatest tonnage per motion that the fabric is capable of handling. Endurance, cost to install and cost to operate also are important factors in the problems.

In handling package freight not so much progress has been made because of the multiplex sorting and distributing necessary and the great variety of forms in which package freight appears. However, machinery is being rapidly developed that can cope with the varied requirements of freight terminals and because of the novelty of this class of motor application it is little understood or appreciated as a prospective power load.

The principal methods used in this branch of the work are:

Storage battery vehicles, such as—

Commercial trucks.
Industrial or battery trucks.
Battery truck cranes.
Battery tractors with trailers.

All these machines require battery charging equipments and consume (due to the low over-all efficiency) much more power than their output would indicate. From the user's standpoint, however, the current consumed is of very minor importance compared with the advantages gained by being able to move the tool about, independent of any power circuit.

Monorail apparatus composed of trolley cars suspended from a single overhead rail and equipped with winches and various devices for lifting and carrying freight.

Conveyers, either fixed or sectionalized and portable; operated from fixed circuits or flexible cables run to nearby power services. These machines have simple motor and control problems and are becoming popular wherever quantities of packages are moved moderate distances.

Derricks are used to a great extent in the loading and discharging of ships and lighters; usually steam-driven but lately largely actuated by portable or fixed electric winches on wharves. High speed with reliable braking and moderate load capacity are their usual characteristics and the control features are capable of giving greater convenience, safety and dispatch than the ordinary steam winch with crank throttle, foot brake and reverse mechanism.

Winches are applied in a variety of ways to warehouse work, wharf work and shipping in general, as they take advantage of the universal wire rope and hook that can go anywhere after a package and bring it out.

Cranes used in package freight handling are varied in design and manner of doing their work—not very largely adopted in this country, but being more and more widely considered. A number of motors are required on each crane to accomplish the various motions with proper efficiency and in the best manner. Some cranes combine conveyer principles in their make-up, giving continuous discharge rather than intermittent drafts.

In the improvement of any terminal the features most sought after are:

Dispatch: For rolling and floating stock earn dividends only while in motion. The welfare of communities depend upon rapid transfer of the commodities that flow according to the laws of supply and demand.

Increased capacity: Because freight movements are subject to peaks of severity and frequence, and unless able to cope with them, congestion often occurs of far reaching consequence and economic loss.

Safety, both to persons and property, is much sought after, as damage claims for lost, broken or spoiled freight amount to a huge sum and injuries to employees are of very common occurrence.

Service: It is the aim of all terminal authorities to increase the service rendered to patrons on account of competition and the new desire to cultivate the good will of the public—" the oxygen for the lungs of business."

Economy: When it is understood how great are the costs of freight handling as compared with freight hauling, it becomes of paramount importance to modernize methods to something of the efficiency attained in hauling. Shipping by sea costs one-half mill per ton-mile, hence a difference in handling, say from 45c. per ton to 12c. per ton (not extraordinary), would equal the cost of hauling from Havana to Boston, or, if by rail at 7½ mills per ton-mile, from Philadelphia to New York.

The costs of handling bulk freight have been reduced in a few years from 40 to 7 cents per ton and while a reduction to this extent cannot be expected in package freight, nearly as good results have been attained in specially favorable classes and lessened gains in other more difficult cases.

The electric motor possesses great advantages over any other known means of actuating these varied devices both for bulk and package work and an outline of these advantages will be in order.

(*a*) It transforms the energy of transmission to energy of useful motion closer to where the motion can be used than any other power device.

(*b*) By virtue of a variety of designs a wide range of characteristics are available. Some are adapted for certain kinds of work and others for different circumstances. Not so with steam, air or water as each has fixed characteristics.

(*c*) Nicety of control is inherent with electric devices. Speeds under the various circumstances can be determined and set in advance. Braking can be regulated and applied surely without effort on the operator's part. Acceleration is automatically regulated as are the various other functions of the apparatus. Remote control is easily arranged so that operators can see their work and even go along with it. Motors may be widely scattered to do their work best but the control of all can be brought to the most sightly place for one man's convenience.

(*d*) Power can be subdivided into comparatively minute portions without sacrificing efficiency, thus accommodating small power requirements so often prevailing in package freight work.

(*e*) Greater speed is attainable with electric drives because of less effort on the part of the operator, more nearly automatic operation thus eliminating the personal equation and by the characteristics of the motor being such as to take advantage of every part of the cycle to increase speed.

(*f*) Terminal capacities are increased by the electric motor through the general speeding up of movements, the use of small units in piling and economical stowing of goods, elimination of congestion periods by virtue of its capability to cope with unusual loads for long periods and by rendering available superimposed areas as contrasted with the usual ground level working area of terminals.

(*g*) Safety goes hand in hand with electric motor methods, due to the automatic features, quickness of control and convenience of control locations. Not the least aid to safety in terminals is adequate lighting, though not a motor application it should nevertheless be more common and more intense.

(*h*) Electrically equipped terminals offer greater service to patrons by quicker readiness to deliver and receive goods. Commodities are delivered with fewer damages and in more cleanly condition than prevails when hand methods are used. Reservoir effects are increased, *i.e.*, terminals act as pools or reservoirs in traffic flow and thereby render a service augmented by electrical machinery, which increases the pool capacity and hastens the filling and emptying work.

(*i*) The greatest degree of economy is invariably found in electrified terminals, since motors can do for little money what many men ordinarily do for much money. They eliminate troubles incident to the employment of large numbers of unskilled men and the use of ingenious machinery raises the standard of employees and increases their loyalty by eliminating the animal-like drudgery common to the old terminal.

If it were possible to do so, without more misleading effect than aid, some data would be added regarding watts per ton, but there are so many widely varying conditions, such as weight of units, weight of drafts, vertical distance, horizontal distance, rate of motion and auxiliary work such as checking, weighing and inspecting, that interfere with uniform results. In general, the cost of current is negligible as compared with the over-all cost of the large labor force always necessary, the overhead cost of terminal facilities and clerical force and the standby charges of floating and rolling property. However, the power used does aggregate a large amount when taken in connection with adequate lighting of terminal areas, and at least that part that goes to charge batteries is off-peak and very desirable.

Motor applications in freight handling are bound to increase rapidly as terminals are so hemmed in by high-priced property as to preclude ordinary expansion, and intensive cultivation of present areas must follow. The electric motor is the logical and accepted tool for carrying on this betterment.

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CLASSIFICATION OF ALTERNATING-CURRENT MOTORS

BY VAL A. FYNN

Abstract of Paper

This paper points out that in order to arrive at a rational classification of alternating-current motors it is necessary to base all suggestions on one and the same theory. The author thinks that the component field theory is best suited to this purpose, and urges that it be always so applied as to bring out the very great similarity between the alternating- and the well understood direct-current machines.

Descriptive names are suggested for some 44 alternating-current motors, including the principal forms of single-phase, polyphase, commutator and commutatorless machines now known. These names are such as to positively identify each of these machines. The rules followed in preparing the diagrams illustrating the various forms of motors and in selecting the proposed names, are given. In order to enable the reader to quickly judge of the aptness of these names, the theory of each of the motors dealt with is briefly outlined. It is thought that the information given will make it easy to correctly represent, describe and classify any motor which may have been omitted.

It is further pointed out that the term "repulsion" as applied to motors, has never been defined, that no practical motors operate on what has been known as the repulsion principle ever since 1820, and that there is no justification whatsoever for the use of this term in connection with alternating-current motors. Such an indefinite term leads merely to endless confusion and should be abandoned. If it is not abandoned, it should be given a rational and definite meaning.

THE OPERATION of dynamo-electric machines can always be explained in one of two ways; either by considering the resultant magnetic field, or by dealing with each of the component fields separately throughout the investigation. Both methods lead to correct results provided each is handled with equal skill and accuracy. But it has been my uniform experience that the resultant field theory is much more difficult to apply to alternating-current commutator motors, and although the final result is as correct as that obtained by what may be termed the component field theory, yet the latter gives a very much clearer insight into the intermediate stages, and I believe, approximates much more closely the actual facts. As an illustration, I may state that although I had devoted a number of years to the careful study of single-phase motors of all types, yet I was unable to make any appreciable progress until, in the 90's, I developed a component field theory of these machines, based on the theory of the ordinary direct-current motor. I firmly believe that students of the present day find themselves in exactly the same position. When the so-called " repulsion motor " is first brought to their attention, they no doubt imagine that they are faced with a machine which stands in a class all by itself and has no relation whatsoever to those with which they are already familiar. The component field theory, based on the theory of the ordinary direct-current motor, immediately dispels this illusion and brings home to the student the fact that the so-called repulsion motor is nothing but an alternating-current form of the well-known direct-current series machine. I find that this theory makes it possible to positively and readily identify each of the many single and polyphase motors with and without commutators. An identification based on this theory may, in some cases, require quite a number of words, but there can be nothing astonishing in this fact if it is remembered that a great many of the alternating-current commutator motors only differ from each other in the matter of detail. Knowing of no rational way of more shortly describing such motors except by using coined expressions or by sacrificing accuracy and positiveness, I base the terminology and classification here proposed on the component field theory above referred to.

In the following I will give the rules which I have followed in preparing the appended diagrams and in suggesting names for the various motors which they illustrate. I will also give a short outline of the manner in which each of the motors operates, thus making it easily possible for the reader to judge of the aptness of the suggested designation.

Rules Followed in Preparing Diagrams and in Suggesting Names for the Various Types of Motors

1. *A commuted winding* is represented by a thick circle and is always assumed to be a "left-hand" Gramme ring winding. The brushes are supposed to rest directly on the winding. commutator and commutator connections being dispenced with. The direction of the armature reaction flux is indicated by a straight arrow marked *R*. In the case of a " left-hand " Gramme ring winding the direction of the flow of current from brush to brush corresponds with the direction of the armature reaction flux set up by said current. See Fig. 1.

2. *A distributed stator winding* is indicated by a number of concentric turns with the same axis as that of the resultant magnetization produced by the distributed winding it represents. See winding *F* of Fig. 2.

3. ***A unicoil stator winding*** is represented by a number of concentric turns and the legend "unicoil." When a winding may be either distributed or unicoil without materially influencing the operation of the machine, the legend " or unicoil " may be added.

4. ***A stator winding*** adapted to inductively convey working energy to the rotor is marked *W*.

5. ***A stator winding*** adapted to inductively convey working and exciting energy to the rotor is marked *S*.

6. ***A stator winding*** adapted to inductively convey exciting energy to the rotor is marked *E*.

7. ***A neutralizing winding*** is one producing a flux opposed in direction to the armature reaction flux. It is usually disposed on the stator and is marked *N*.

8. ***An exciting winding*** is one producing or contributing to the production of the motor, or torque producing, field. When located on the stator it is marked *F*.

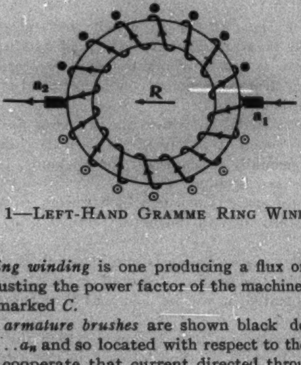

FIG. 1—LEFT-HAND GRAMME RING WINDING

9. ***A compensating winding*** is one producing a flux or generating an e.m.f. used for adjusting the power factor of the machine. When located on the stator it is marked *C*.

10. ***Working or armature brushes*** are shown black designated by the letters a_1 a_2 .... a_n and so located with respect to the (rotor) winding with which they cooperate that current directed through said winding by the working brushes. produces nothing but working or armature ampere-turns.

11. ***Exciting or field brushes*** are shown white, designated by the letters f_1 f_2 .... f_n and so located with respect to the (rotor) winding with which they cooperate that current directed through said winding by the exciting brushes produces nothing but exciting ampere-turns.

12. ***Brushes*** so located with respect to the (rotor) winding with which they cooperate that current directed by them produces armature or working as well as exciting ampere-turns in said winding, are shown sectioned. and designated by the letters b_1 b_2 .... b_n.

13. ***A shunt transformer*** is designated by the letter *T*.

14. ***A series transformer*** is designated by the letters *ST*.

15. ***Current directed up*** through the paper is shown by a circle with a dot in its center.

16. *Current directed down* through the paper is shown by a totally filled-in circle.

17. *The direction of rotation* of the motor is shown by a curved arrow.

18. *The direction of the working or exciting current through a stator winding* is indicated by a straight arrow placed alongside said winding. In the case of polyphase motors arrows alongside windings belonging to different phases, show the direction of the current in said windings at a time interval of $180/n$ degrees, where n is the number of phases.

19. *The direction of the motor field produced by a rotor winding* is indicated by a straight arrow marked *Fr*.

20. *The armature or working axis* is always placed vertically, *the exciting axis horizontally*, in single-phase motors.

21. The word *commutator* may be omitted in describing a motor having a commutator, provided no equivalent commutatorless machine is known.

22. *A conduction motor* is one in which the energy required by its armature, generally the rotor, is conveyed to it by conduction. When nothing to the contrary is stated, it will be assumed that the machine spoken of *is* of the conduction type.

23. *An induction motor* is one in which the energy required by its armature, generally the rotor, is conveyed to it by induction.

24. *A series motor* is one in which the field excitation varies in some proportion with the armature current, and the speed of which, therefore, varies with varying load.

25. *A shunt motor* is one in which the working and exciting e.m.f.'s remain practically constant independently of the load. The speed of such motors will generally be constant for all loads, but will not necessarily be a nearly synchronous one.

26. *A compensated motor* is one in which means, other than a neutralizing winding, are provided for adjusting (improving) the power factor of the machine.

27. *A motor with stator excitation* is one in which the motor, or torque-producing, field is due to a winding disposed on the stator. When nothing to the contrary is stated, it will be assumed that the motor in question *has* stator excitation.

28. *A motor with rotor excitation* is one in which the motor or torque-producing, field is due to a winding located on the rotor

29. *A separately-excited motor* is one in which the field excitation is derived from the mains, either directly or through the agency of apparatus which is independent of the motor itself, and whether the exciting current is taken to a winding on the rotor or on the stator. When nothing to the contrary is said, it will be assumed that the motor *is* separately-excited.

30. *A self-excited motor* is one in which the exciting current is due to an e.m.f. generated in the motor itself by induction. Such an e.m.f. may be generated in the rotor by rotation in a flux, or by static induction from the stator, or it may be generated in the stator by static induction from the rotor, or from the stator.

31. *A motor with mixed excitation* is one which is separately as well as self-excited.

32. *A conductively-neutralized motor* is one in which the armature re-

action flux is neutralized by means of a winding (generally located on the stator) connected in series relation with the armature brushes. In speaking of such a machine it will be sufficient to refer to it as a ***neutralized motor***.

33. ***An inductively neutralized motor*** is one in which the circuit of the neutralizing winding is closed independently of the armature brushes and is placed in inductive relation to the armature reaction flux. Note that an induction motor is *ipso facto* an inductively neutralized motor.

34. ***A motor with independent brushes*** is one in which brushes which are not interconnected and not connected to the supply so cooperate with the commutator as to each short circuit a number of the coils of the commuted winding.

35. ***A single-phase motor*** is one which receives the whole of the working energy it requires from only one phase of an alternating-current supply. It may receive its exciting energy from the same or from another phase.

36. ***A polyphase motor*** is one which receives working energy from a plurality of phases of an alternating-current supply.

37. When diagrams represent machines with more than two poles, a legend to that effect should appear.

PROPOSED NAMES AND THEORY OF OPERATION

Motors with Series Characteristic

Single-Phase Series (Conduction)* *Motor*. Fig. 2.

Two co-phasal fluxes, R and F, are set up in this machine The flux R is due to the rotor ampere-turns. The flux F is located at 90 electrical degrees to R, and is due to the stator ampere-turns F. R performs no useful work. F cooperates with all the rotor ampere-turns to produce the motor torque and is therefore the motor flux or field. Energy is conveyed to armature and field windings conductively. The back e.m.f. is generated in the armature conductors by rotation in the motor field and appears at the brushes a_1 a_2. The machine has a series characteristic, because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns, and the torque per ampere is independent of the power factor. The machine does not possess any inherent power-factor-improving qualities; in other words, it is not self-compensating. Its power factor

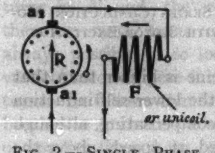

Fig. 2 — Single-Phase Series (Conduction) Motor

is low at all speeds, principally because of the high armature inductance, but rises with increasing speed. The machine may be reversed by changing the direction of the current through the armature or through F. The stator may or may not have defined polar projections. The field winding may be of the distributed or of the unicoil type.

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*Terms included in brackets are not supposed to form part of the proposed name and are added merely for the sake of explanation.

Neutralized Single-Phase Series (Conduction) *Motor.* Fig. 3.

This differs from the motor shown in Fig. 2, only in that the armature reaction flux R, which performs no useful work, is neutralized by means of the stator winding N located and dimensioned to produce a flux equal and opposite to R. The neutralizing winding N is in conductive relation to the armature circuit and should be of the distributed type in order to secure the best results. The power factor of this machine is higher than that of the one shown in Fig. 2, because of the lower self-induction of the rotor, but the machine is not self-compensating, although very high power factors can be reached at speeds above the synchronous.

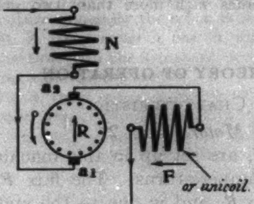

Fig. 3—Neutralized Single-Phase Series (Conduction) Motor

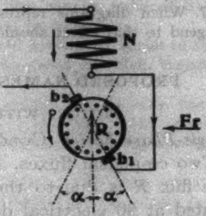

Fig. 4—Neutralized Single-Phase Series (Conduction) Motor with Rotor-Excitation

Neutralized Single-Phase Series (Conduction) *Motor with Rotor-Excitation.* Fig. 4.

There are three-cophasal fluxes, N, R and Fr, in this machine. The flux N is due to the stator ampere-turns N, each of the others is due to part of the rotor ampere-turns. The total rotor ampere-turns exceed the stator ampere-turns, and the brushes b_1 b_2 are so displaced with respect to the axis of N that the flux R due to the rotor ampere-turns comprised within the angle $360 - 4\alpha$ degrees equals and opposes N. The remaining rotor ampere-turns comprised within the angle 4α produce the flux Fr at 90 electrical degrees to the two others. The rotor ampere-turns distributed along those parts of the rotor circumference which are distinguished by heavier lines $(360 - 4\alpha)$ do duty as armature ampere-turns. The remaining rotor ampere-turns $(4\ \alpha)$ do duty as field ampere-turns, producing the only really existing field Fr of the machine. Fr is the motor field, it co-operates with the armature ampere-turns on the rotor to produce the motor torque. Energy is conveyed to armature and field windings conductively. The back e.m.f. is generated in the armature conductors of the rotor $(360 - 4\alpha)$ by rotation in the motor field Fr. The machine has a series characteristic because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns, and the torque per ampere is independent of the power-factor. The machine is not self-compensating, but its power factor rises with increasing speed. It may be reversed by moving the brushes through $2\ \alpha$ degrees against the direction of the initial rotation; this reverses the direction of the motor field but not that of the armature ampere-turns on the rotor. The stator may or may not have defined polar projections. The neutralizing winding should preferably be of the distributed type.

Because of the *conductive relation* between stator and rotor windings in Fig. 4, there is no fixed relation between the ampere-turns in N and the coaxial rotor ampere-turns. Provided there are more turns on the rotor than on the stator, it is always possible to so locate the brushes b_1 b_2 as to make the vertical rotor ampere-turns equal and opposite to the N ampere-turns. It follows that it must also be possible to so locate said brushes as to make the vertical rotor ampere-turns either larger or smaller than those of N. It should be noted that no such condition can be secured in case the relation between stator and rotor windings is inductive instead of conductive.

When the rotor turns exceed those of N, a value of α differing from zero can be found for which the vertical rotor ampere-turns are greater than the N ampere-turns. In such a case a flux $R\ N$ will be present along the axis of N, in addition to the motor field Fr along the horizontal axis. This additional flux $R\ N$ cooperating with the rotor ampere-turns responsible for Fr and located within 4α degrees, will develop a *negative* torque, *i.e.*, one opposed in direction to that due to the interaction of

Fr and of the armature ampere-turns $(360 - 4\alpha)$ on the rotor. Otherwise the machine will behave as before.

If α is so chosen as to make the vertical rotor ampere-turns smaller than those of *N*, then a flux *N R* will be present along the axis of *N* in addition to *Fr* in the horizontal axis, and the flux *N R* cooperating with the rotor ampere-turns responsible for *Fr*, will develop a *positive* torque. Otherwise the machine will behave as before.

Inductively-Neutralized Single-Phase Series (Conduction) *Motor.* Fig. 5.

This machine differs from that shown in Fig. 3 only in that the neutralizing winding *N* is in inductive instead of conductive relation to the armature ampere-turns. A motor of this kind must always be under neutralized, since no current can be induced in *N* unless a flux of mutual induction is present, which flux must be supplied by armature ampere-turns. A conductively neutralized motor (Fig. 3) can, on the other hand, be neutralized or over neutralized to any desired degree. The lower the ohmic resistance of *N* in Fig. 5, and the better its inductive relation to the armature ampere-turns, the more complete the neutralization of the armature self-induction. The flux of mutual induction along the brush axis only affects the commutation. The machine shown in Fig. 5 otherwise operates just the same as that illustrated in Fig. 3.

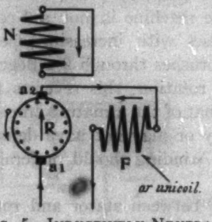

FIG. 5—INDUCTIVELY-NEUTRALIZED SINGLE-PHASE SERIES (CONDUCTION) MOTOR

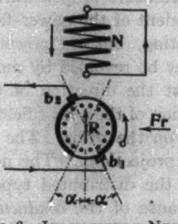

FIG. 6—INDUCTIVELY NEUTRALIZED SINGLE-PHASE SERIES (CONDUCTION) MOTOR WITH ROTOR-EXCITATION

Inductively-Neutralized Single-Phase Series (Conduction) *Motor with Rotor-Excitation.* Fig. 6.

There are four fluxes to be considered in this machine: A vertical flux of mutual induction due to a magnetizing current circulating in the rotor; a vertical armature reaction flux R due to the true rotor working current; an equal and opposite flux due to the current induced in N; and a horizontal flux Fr due to the total rotor current, *i.e.*, to the vectorial sum of rotor magnetizing and working currents. R and N perform no useful work and cancel each other. Fr cooperates with the total rotor ampere-turns comprised within $360 - 4\,\alpha$ degrees, to produce the main motor torque. The vertical flux of mutual induction is usually very small because of the low impedance of N. This flux affects commutation and produces a subsidiary torque with the total rotor ampere-turns responsible for Fr and located within $4\,\alpha$ degrees. This subsidiary torque is negative and dminishes rapidly with increasing speed, reaches zero, and may become positive. It is small at any time because of the smallness of the vertical flux of mutual induction. By rotation of the motor field producing turns ($4\,\alpha$) in said flux, an e.m.f. is generated in the rotor which increases its impedance, thereby lowering the power factor of this machine. This effect is, however, small because the vertical flux of mutual induction is small at all speeds and decreases with increasing speed.

Energy is conveyed to armature and field windings conductively. The back e.m.f. is generated in the armature conductors comprised within $360 - 4\,\alpha$ degrees by rotation in the motor field produced by the rotor conductors comprised within $4\,\alpha$ degrees. The machine has a series characteristic, because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns and the torque per ampere is independent of the power factor. The power factor is slightly worse than that of Fig. 5. The machine may be reversed by moving the brushes past the axis of N and against the initial direction of rotation. It should be noted that because of the inductive relation between rotor and stator the total rotor ampere-turns, as well as those in the axis of N, must always exceed the ampere-turns in N, regardless of the magnitude of α. The stator may or may not have defined polar projections. The neutralizing winding should be distributed.

Inductively-Neutralized Single-Phase Series (Conduction) *Motor with two Conductively Related Rotor Circuits*. Fig. 7

The mode of operation and characteristics of this machine are identical with those of the previous one, with this difference, that the armature and the field ampere-turns on the rotor are produced in independent but conductively linked rotor windings. One of these does exclusive duty as armature and the other exclusive duty as field winding. This machine may be reversed by reversing the current through the rotor armature winding cooperating with the brushes a_1 a_2, or through the rotor field winding cooperating with the brushes f_1 f_2.

Neutralized Series (Conduction) *Motor with two Inductively Related Rotor Circuits.* Fig. 8.

The mode of operation and characteristics of this machine are identical with those of the one shown in Fig. 4, with this difference, that the whole of the rotor winding is made use of as armature winding along one axis and as field winding along an axis at right angles to the first. To this end, independent armature or working brushes a_1 a_2 and field or exciting brushes f_1 f_2 are used, the two rotor circuits being inductively linked by means of a series transformer $S\ T$. Whether an additional torque is produced between the field armpere-turns and the flux $R\ N$ or $N\ R$ depends on the number of turns in N. The direction of rotation may be reversed by reversing the current through the working circuit N, a_1 a_2, $S\ T$, or the exciting circuit f_1 f_2, ST.

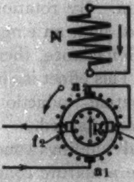

FIG. 7—INDUCTIVELY-NEUTRALIZED SINGLE-PHASE SERIES (CONDUCTION) MOTOR WITH TWO CONDUCTIVELY RELATED ROTOR WINDINGS

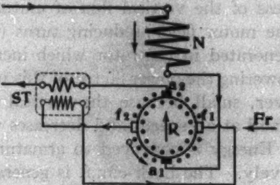

FIG. 8—NEUTRALIZED SERIES (CONDUCTION) MOTOR WITH TWO INDUCTIVELY RELATED ROTOR CIRCUITS

Neutralized and Compensated Series (Conduction) *Motor with two Inductively Related Rotor Circuits.* Fig. 9.

This motor differs from the previous one only in that the compensating winding C has been added. The flux produced by C lags about 90 electrical degrees behind the terminal e.m.f.; it affects the commutation under the brushes a_1 a_2, cooperates with the exciting ampere-turns on the rotor to produce an auxiliary torque, and is responsible for a compensating speed e.m.f. appearing at the brushes f_1 f_2 and of course due to the rotation of the rotor conductors in the flux *C*. At starting, the effect of *C* on commutation is negligible, and it has no phase-compensating influence, but contributes an appreciable and positive auxiliary torque. As the speed increases the auxiliary torque diminishes, and may reverse, but the compensating effect and the influence of *C* on the commutation increase.

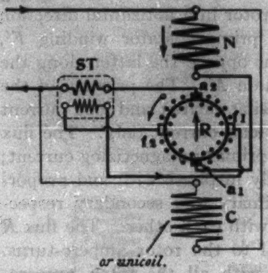

FIG. 9—NEUTRALIZED AND COMPENSATED SERIES (CONDUCTION) MOTOR WITH TWO INDUCTIVELY RELATED ROTOR CIRCUITS

Single-Phase Series (Conduction) *Motor with Mixed* (Stator) *Excitation*. Figs. 10 and 11.

This machine, devised in 1888,* is one of the earliest single-phase commutator motors, but is somewhat difficult to represent diagrammatically along the lines adopted in all other cases; one attempt in this direction is illustrated in Fig. 11.

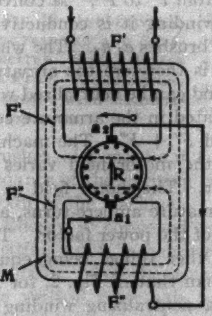

FIG. 10—SINGLE PHASE SERIES (CONDUCTION) MOTOR WITH MIXED (STATOR) EXCITATION

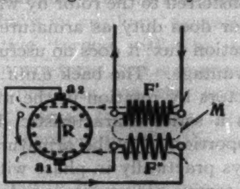

FIG. 11—SINGLE-PHASE SERIES (CONDUCTION) MOTOR WITH MIXED (STATOR) EXCITATION

Referring more particularly to Fig. 10, there are four fluxes to consider: A flux of mutual induction *M* linking the primary stator winding *F'* connected to the mains with the secondary stator winding F'' connected to the rotor winding. This flux closes without passing through the rotor. A flux R due to the rotor ampere-turns and threading the rotor in a vertical direction. A flux F'' threading the rotor in a horizontal direction and due to the ampere-turns in the secondary stator winding F''. A flux F' also threading the rotor in a horizontal direction but due to ampere-turns in the primary stator winding F', which are equal to those in F'' but oppose the latter along the path of the flux of mutual induction M. The primary of the transformer F' F'' carries magnetizing current and load current as is usual; the secondary carries load current only. The flux M is practically in phase with the primary magnetizing current; the fluxes F' and F'' are practically in phase with and proportional to the load currents in primary and secondary respectively, and are therefore in phase with each other. The flux R is in phase with and proportional to the rotor ampere-turns. The fluxes F' and F'' cooperate with all the rotor ampere-turns and produce the motor torque, and are therefore the motor fields. The field excitation is derived in part directly from the mains through the primary F', and is in part generated in the rotor itself by static induction from F' to F'', M conveys energy from F' to F'', from which winding it is conductively transferred to the rotor by way of the brushes a_1 a_2. The whole rotor does duty as armature, and R is therefore the armature reaction flux; it does no useful work and can be neutralized with advantage. The back e.m.f. is generated in the armature conductors by rotation in the motor field $F' + F''$. The machine has a series characteristic, because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns, and the torque per ampere is independent of the power factor. The machine is not self-compensating. Other things being equal, its power factor is somewhat lower than that of Fig. 2, for instance, because of the flux M. If a neutralizing winding is added, the power factor will be comparable with that of the motors shown in Fig. 3 or 5. The machine may be reversed by changing the direction of the current through the armature. The stator should have defined polar projections. The field windings should be of the unicoil type. This machine is really a combination of a reducing transformer with a motor. The primary and secondary windings of the transformer also do duty as field exciting windings for the motor, the rotor of which receives its energy from the secondary of said transformer by conduction.

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*See U. S. P. 591,301.

Inductively-Neutralized and Self-Excited Single-Phase Series (Conduction) *Motor with Rotor-Excitation.* Fig. 12.

Four fluxes are to be considered: A vertical flux of mutual induction linking rotor and stator windings and due to a magnetizing current circulating through the rotor; a vertical armature reaction flux *R* due to what may be referred to as the true rotor working current; an equal and opposite flux due to the current induced in *N*; and a horizontal flux *Fr* due to the current induced in *N* but circulating through the rotor along the axis f_1 f_2. *R* and *N* perform no useful work and cancel each other. *Fr* cooperates with the total vertical rotor ampere-turns, *i.e.*, those due to the rotor magnetizing as well as to the true rotor working current, to produce the main motor torque. The vertical flux of mutual induction is large, because of the high impedance of the exciting circuit f_1 f_2, fed by the neutralizing winding *N*. Said flux affects the commutation under the working brushes a_1 a_2, produces an auxiliary, appreciable and negative torque with the rotor exciting ampere-turns, and is responsible for the appearance, at the exciting brushes, of a speed e.m.f. of such phase as to increase the impedance of the exciting circuit and therefore to lower the power factor of the machine.

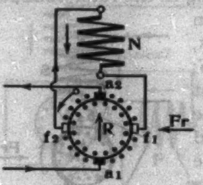

FIG. 12—INDUCTIVELY-NEUTRALIZED AND SELF-EXCITED SINGLE-PHASE SERIES (CONDUCTION) MOTOR WITH ROTOR-EXCITATION

Energy is conveyed to the armature by conduction. The exciting e.m.f. is generated in the neutralizing winding *N* by induction from the rotor. The back e.m.f. is generated in the vertical rotor axis by rotation of the rotor conductors in *Fr*. The machine does not possess a true series characteristic because of the strong negative and irregularly varying torque due to the vertical flux of mutual induction, and because the phase relation between *Fr* and the vertical rotor ampere-turns is a variable one. The power factor is low at all speeds. The machine may be reversed by reversing the connections between *N* and the horizontal rotor axis. The general performance is very poor.

Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation. Fig. 13.

The theory of this machine becomes self-evident the moment one realizes that the only difference between it and the motor shown in Fig. 4, is that, in the latter, energy is conveyed to the rotor by conduction whereas in this case it is conveyed to the rotor by induction. In order to convert Fig. 4 into Fig. 13, it is, indeed, only necessary to short circuit the brushes b_1 b_2.

There are four fluxes to consider. A vertical flux of mutual induction (transformer flux) due to a magnetizing current circulating in the primary or stator winding *S*; a vertical rotor flux *R* due to the current induced by the transformer flux in the short circuited secondary or rotor and circulating in the rotor conductors located within $360-4\alpha$ degrees; an equal and opposite, *i.e.* neutralizing, flux, due to the corresponding current in *S*; and a horizontal flux *Fr* due to the current induced in the rotor and circulating in the conductors located within 4α degrees and therefore out of inductive relation with the stator winding *S*. The flux *R* and the opposing stator flux are co-phasal with the flux *Fr*; they cancel each other and therefore perform no useful work. *Fr* cooperates with the rotor conductors responsible for *R* $(360-4\alpha)$ in producing the main motor torque. The vertical flux of mutual induction cooperates with the rotor conductors (4α) responsible for *Fr* to produce an auxiliary and positive torque, which diminishes as the power factor of the motor improves. This flux is also responsible for a speed e.m.f., generated by rotation in said flux of the rotor conductors located within 4α degrees. This e.m.f. is of a phase adapted to decrease the rotor impedance, thus improving the power factor of the motor. This inherent quality cannot raise the power factor to unity, but it improves it materially, thus rendering the machine *self-compensating.* This self-compensation increases with increasing transformer flux and speed.

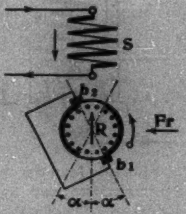

Fig. 13—Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation

Energy is conveyed to the rotor conductors doing duty as armature $(360-4\alpha)$ and to those doing duty as field windings (4α), inductively. The back e.m.f. is generated in the armature conductors by rotation in *Fr*; it reduces the current in the secondary (rotor) and increases the flux of mutual induction, linking the rotor with the primary *S*. The machine has a series characteristic because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns, and the main torque is independent of the power factor. The auxiliary torque is too small to materially affect the torque characteristic within the normal speed range. The power factor rises to near unity at about synchronism. The machine may be reversed by moving the brushes though α degrees against the direction of the initial rotation, whereby the direction of *Fr* only is reversed. The stator should have no defined polar projections, and the stator winding should be distributed.

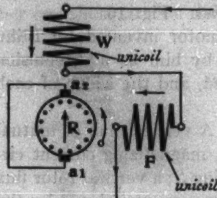

FIG. 14—SINGLE-PHASESERIES INDUCTION MOTOR (WITH STATOR-EXCITATION)

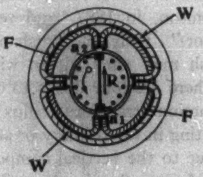

FIG. 15—SINGLE-PHASE SERIES INDUCTION MOTOR (WITH STATOR-EXCITATION)

Single-Phase Series Induction Motor (with Stator-excitation) Figs. 14 and 15.

The actual distribution of the stator windings diagrammatically indicated in Fig. 14, is shown in Fig. 15. It is clear that *F* can have no statically inductive effect on the rotor winding which can make itself felt within the brush circuit, but the rotor will be fully responsive to the inductive effect of *W*. There are four fluxes to consider: A transformer flux due to a magnetizing current in *W*; an armature reaction flux *R* due to the ampere-turns induced by *W* in the rotor; an equal and opposite flux due to the corresponding neutralizing ampere-turns in *W*; and an exciting flux *F* due to the stator magnetizing and neutralizing currents flowing through *F*. The flux *R* is neutralized by the opposing flux due to *W* and does no useful work. The flux of mutual induction affects the commutation only. *F* produces the motor torque in cooperation with all of the rotor mpere-turns.

Energy is conveyed to the armature inductively and to the field winding conductively and directly from the mains. The back e.m.f. is generated in the armature conductors by rotation in the motor field and appears at the brushes a_1 a_2; it decreases the rotor current and increases the transformer field. The machine has a series characteristic because the motor field varies practically in proportion with the armature current at all but very light loads. The motor field is always a little out of phase with the armature current, and the torque per ampere is almost independent of the power factor, which is low at all speeds. The machine may be reversed by changing the direction of the current through *F* or through *W*.

Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and Independent Brushes. Fig. 16.

This is the modern form of the motor invented by Elihu Thomson, in 1887,* and referred to by him as a "repulsion motor." Only one brush may be used, and the width of each brush may vary within wide limits.

There are four fluxes to consider: A vertical flux of mutual induction (transformer flux) due to a magnetizing current circulating in the primary or stator winding *S*; a vertical rotor flux *R* due to the vertical component of the current induced by the transformer flux in the coils short circuited by the brushes *b*; an equal and opposite, *i.e.*, neutralizing, flux due to the corresponding current in *S*; and a horizontal flux *Fr* due to the horizontal component of the current induced in the short circuited rotor coils. The flux *R*, the opposing stator flux, and *Fr* are co-phasal; the first two cancel each other and therefore perform no useful work. *Fr* cooperates with the rotor ampere-turns responsible for *R* to produce the main motor torque. The vertical flux of mutual induction cooperates with the rotor ampere-turns responsible for *Fr*, to produce a positive auxiliary torque which diminishes as the power factor improves. By revolution of the rotor conductors in this transformer flux, a compensating e.m.f. is generated within the rotor short circuits, tending to raise the power factor of the machine.

Working and exciting energy is conveyed to the rotor by induction. The back e.m.f. is generated in the rotor short circuits by rotation in *Fr*, and tends to decrease the rotor current and increase the flux of mutual induction. The machine has a series characteristic, because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns, and the torque per ampere is independent of the power factor. The power factor is good at speeds near the synchronous. The machine may be reversed by shifting the brushes into the other quadrants. This machine is not now used; it is much inferior to that shown in Fig. 13, although it has the same general characteristics as the latter.

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*See U. S. P. 363, 185.

Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and two Independent Rotor Circuits. Fig. 17.

This machine operates exactly like that shown in Fig. 16, but utilizes the rotor copper much more efficiently and with much smaller friction losses. Electrically, the result is the same whether one short circuits the brushes b_1 b_2 by means of a conductor or replaces them by a single brush covering the arc previously short-circuited by the two interconnected brushes. The arrangement shown in Fig. 17 is practical and allows of a wide regulation of the motor, for instance by moving the brushes b_2 and b_3.

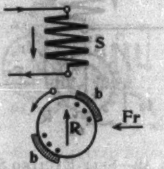

Fig. 16—Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and Independent Brushes

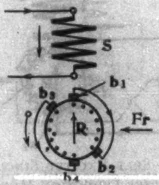

Fig. 17—Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and Two Independent Rotor Circuits

Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and two Inductively Related Rotor Circuits. Fig. 18.

The mode of operation and characteristics of this machine are identical with those of the one shown in Fig. 13, with this difference, that the whole of the rotor winding is made use of as armature winding along one axis and the whole of it is made use of as field winding along an axis at right angles to the first. To this end, independent brushes f_1 f_2 are used, the two rotor circuits being inductively linked by means of the series transformer *ST*. The direction of rotation may be reversed by reversing the direction of the exciting current, which is done by changing the connections between *ST* and the brushes $f_1 f_2$.

Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and two Conductively Related Rotor Circuits. Fig. 19.

The mode of operation and characteristics of this machine are identical with those of the previous one, with this difference that the armature and the field ampere-turns on the rotor are produced in independent but conductively-linked rotor windings. One of these does exclusive duty as armature and the other exclusive duty as field winding. This machine may be reversed by reversing the current through the rotor winding doing duty as field winding. The machine is less flexible than that shown in Fig. 18, because of the absence of the transformer, which can of course be of the adjustable ratio type.

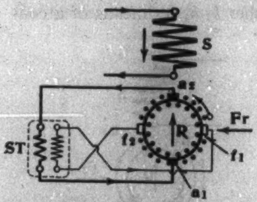

Fig. 18—Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and Two Inductively Related Rotor Circuits

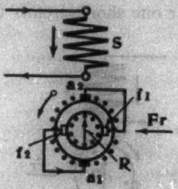

Fig. 19—Self-Excited Single-Phase Series Induction Motor with Rotor-Excitation and Two Conductively Related Rotor Windings

Self-Excited Single-Phase Series Induction Motor (with Stator-Excitation). Fig. 20.

Four fluxes must be taken into account: A vertical flux of mutual induction due to a magnetizing current in *S*; a vertical armature reaction flux *R* due to the ampere-turns induced in the rotor by *S*; an equal and opposite flux due to corresponding ampere turns in *S*; and a horizontal flux due to the stator winding *F* through which is sent the current induced in the rotor by *S*. The flux *R* and the corresponding stator flux cancel each other. *F* cooperates with all the rotor ampere-turns to produce the motor torque. The flux of mutual induction affects only the commutation.

Working and exciting energy is conveyed to the rotor from S by induction. The back e.m.f. is generated in the rotor, *i.e.*, armature conductors, by rotation in the motor flux F. The machine has a series characteristic, because the motor field varies in proportion with the armature current. The motor field is always practically in phase with the armature ampere-turns and the torque per ampere is independent of the power factor. The machine is not self-compensating; its power factor is lower than that of Fig. 13, for instance, but increases with rising speed. The machine may be reversed by reversing the direction of the current through the stator field winding.

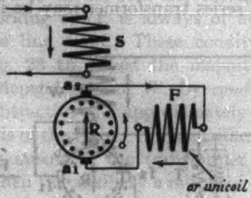

FIG. 20—SELF-EXCITED SINGLE-PHASE SERIES INDUCTION MOTOR (WITH STATOR-EXCITATION)

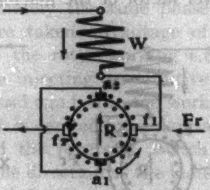

FIG. 21—(SEPARATELY-EXCITED) SINGLE-PHASE SERIES INDUCTION MOTOR WITH ROTOR-EXCITATION

(Separately-Excited) *Single-Phase Series Induction Motor with Rotor Excitation.* Fig. 21.

The mode of operation and characteristics of this machine are readily recognized when it is realized that the only difference between it and the motor shown in Fig. 18, is that the motor flux Fr in that figure is produced by the secondary current of the static transformer $S - a_1 a_2$, whereas in Fig. 21, this flux is produced by the primary current of the transformer $W - a_1 a_2$. While the motor field exciting current in Fig. 18 is strictly in phase with the working current threading the rotor along the vertical axis, and the phase difference between the motor flux Fr and the rotor working ampere-turns amounts merely to the small iron lag of Fr behind the current producing it, in the machine under discussion the phase difference between Fr and the rotor working ampere-turns is increased by the phase difference between the secondary and primary currents of the transformer $W - a_1 a_2$. This phase difference is, of course, due to the magnetizing current in the primary *W*, which is responsible for the flux of mutual induction in the vertical axis, and which conveys the working energy to the rotor. This motor is said to be separately excited, because the exciting energy is taken directly from the mains. The vertical flux of mutual induction is responsible for an auxiliary and positive torque, as in all similar machines, and also for a phase compensating speed e.m.f. which appears at the exciting brushes $f_1 f_2$ and is thus introduced directly into the primary or stator circuit, instead of being first generated in the secondary or rotor circuit, as in Figs. 13 and 16 to 19 inclusive. This speed e.m.f. reduces the impedance of the primary or stator circuit and thus raises the power factor of the machine. A series transformer may be interposed between *W* and the horizontal rotor axis without affecting the mode of operation or the characteristics of the machine; but the use of such a transformer adds to the flexibility of the motor.

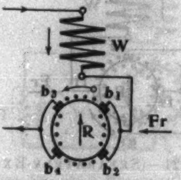

FIG. 22—(SEPARATELY-EXCITED) SINGLE-PHASE SERIES INDUCTION MOTOR WITH ROTOR-EXCITATION

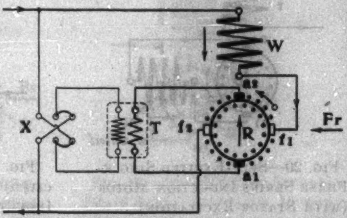

FIG. 23—(SEPARATELY-EXCITED) SINGLE-PHASE SERIES INDUCTION-CONDUCTION MOTOR WITH ROTOR-EXCITATION

(Separately-Excited) *Single-phase Series Induction Motor with Rotor-Excitation*, Fig. 22.

This machine is identical with that shown in Fig. 21, except for the arrangement of the brushes cooperating with the rotor winding. The latter is here short circuited along the lines $b_1 b_2$ and $b_3 b_4$, both of which are parallel to the axis of the stator winding *W*, whereas in Fig. 21, the rotor is short circuited along the very axis of *W*. The current induced in the rotor and producing the armature reaction flux *R*, only circulates in those rotor conductors which are spanned by the two short circuits.

The distribution of this current is shown by dots and circles placed inside the rotor winding. The primary current, producing *Fr*, and conducted through the rotor by way of the short circuited brush groups, only circulates in the remaining rotor conductors, as shown by the dots and circles placed outside the rotor winding. Because the same brushes carry the induced working and the conduced exciting current, they are shown sectioned.

(Separately-Excited) *Single-Phase Series Induction-Conduction Motor with Rotor Excitation.* Fig. 23.

In Fig. 21 the working energy along the working axis is entirely conveyed to the rotor by induction. The entire rotor working e.m.f. in said axis *is induced* in the rotor and depends on and varies with the voltage at the terminals of *W*. This working e.m.f. is always of approximately the same phase as the line e.m.f. These conditions are taken advantage of in Fig. 23 to adjust the magnitude of the rotor working e.m.f. independently of *W*, by *conductively* injecting an additive or subtractive and approximately co-phasal e.m.f. into the working axis of the rotor. This auxiliary e.m.f. is derived from the mains by means of the transformer *T* and the reversing switch *X*. When the auxiliary e.m.f. is of the same direction as the induced working e.m.f., then the vertical axis of the rotor receives energy conductively, as well as inductively. If the direction of the auxiliary e.m.f. is reversed, then part of the energy inductively conveyed to the vertical axis is conductively withdrawn therefrom and conveyed back to the mains. Hence the term "induction-conduction" applied to this machine. Except for the regulation obtained by changing the magnitude or direction of the auxiliary e.m.f. conducted into the vertical rotor axis, the mode of operation and characteristics of the machine are identical with those of the motor shown in Fig. 21.

Neutralized Two-Phase Series (Conduction) *Motor.* Fig. 24.

This is the two-phase equivalent of the single-phase motor shown in Fig. 3. It is obtained by combining two single-phase Fig. 3 motors in one frame and displacing all the elements of one of them by 90 electrical degrees with respect to the corresponding elements of the other. A single rotor winding may be used, as shown in Fig. 24, if interconnection of the phases is permissible. The field winding F_1 of phase 1, does not interfere with the proper working of the armature circuit belonging to phase 2, because any e.m.f. induced by F_1 at the brushes $a_3\, a_4$ is equalled and opposed by an e.m.f. induced by F_1 in N_2. The effect of F_2 on the armature circuit of phase 1, is neutralized in the same manner. The fluxes F_1 and F_2 improve the commutation under speed. The available material is of course far better utilized in Fig. 24 than in Fig. 3.

Neutralized Two-Phase Series (Conduction) *Motor with Rotor-Excitation.* Fig. 25.

This is the two-phase equivalent of the single-phase motor shown in Fig. 4. The brushes b_1 b_2 are displaced by such an angle α from the axis of N_1, that R_1 due to the rotor conductors located within $360 - 4\alpha$ degrees, is neutralized by the flux due to N_1, while the rotor ampere-turns located within $4\,\alpha$ degrees, produce the motor field Fr_1 which co-operates with the rotor ampere-turns responsible for R_1 to produce the motor torque due to phase 1. Similarly, the brushes b_3 b_4 are displaced by such an angle β from the axis of N_2, that R_2 due to the rotor conductors located within $360 - 4\,\beta$ degrees, is neutralized by the flux due to N_2, while the rotor ampere-turns located within $4\,\beta$ degrees produce the motor field Fr_2, which cooperates with the rotor ampere-turns responsible for R_2 to produce the motor torque due to phase 2. The neutralizing windings N_1 and N_2 are displaced by 90 electrical degrees. The two fluxes Fr_1 and Fr_2 improve the commutation under speed.

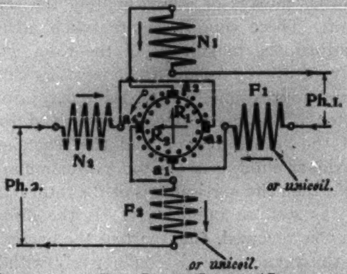

Fig. 24—Neutralized Two-Phase Series (Conduction) Motor

Motors with Shunt Characteristic

In a series machine no difficulty is experienced in obtaining approximate phase coincidence between motor field and armature current, but the conditions for a shunt machine are very different.

Here the chief problem is to provide an exciting e.m.f. of proper phase.

(Separately-Excited) *Single-Phase Shunt* (Conduction) *Motor* (with Stator-Excitation). Fig. 26.

Two fluxes, *R* and *F*, are set up in this machine. If rotor and stator windings are connected to e.m.fs. of the same phase, then the armature ampere-turns set up by the rotor current and responsible for the useless flux *R*, will, at starting, be about in phase with the useful motor flux *F* set up by the stator field winding *F*, for the impedance of both windings is great. The torque per ampere will be good. Energy is conveyed to armature and field windings conductively. The back e.m.f. is generated in the armature conductors by rotation in the motor field. With increasing speed the lag in the armature circuit quickly diminishes, owing to the effect of the dephased back e.m.f., whereby the power factor is improved, but the torque per ampere is reduced. The machine is said to have a shunt characteristic, because the currents in the armature and in the field circuits are quite independent of each other, but the motor speed under varying load is not as constant as is generally desired. This is due to the phase difference between the working and back e.m.fs., which causes the phase relation between working current and motor flux to vary considerably with the load. When the power factor is low, the torque per ampere is high, and vice versa. The weight efficiency of such a machine is so low as to make it commercially useless except in very small sizes and where no importance is attached to constancy of speed. The stator

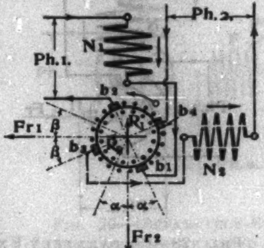

FIG. 25—NEUTRALIZED TWO-PHASE SERIES (CONDUCTION) MOTOR WITH ROTOR EXCITATION

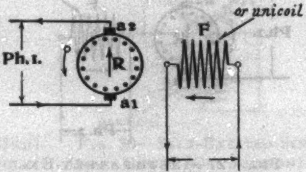

FIG. 26—(SEPARATELY-EXCITED) SINGLE-PHASE SHUNT (CONDUCTION) MOTOR (WITH STATOR-EXCITATION)

may or may not have defined polar projections. The field winding may or may not be of the distributed type.

If rotor and stator windings are connected to e.m.fs. which are in phase quadrature, then the power factor and the torque per ampere are low at starting, and the power factor does not materially change with speed. The speed is more constant, but the weight efficiency is very low.

(Separately-Excited) *Neutralized Single-Phase Shunt* (Conduction) *Motor* (with Stator-Excitation). Fig. 27.

This differs from the foregoing in that the armature reaction flux is neutralized. The armature circuit, comprising the rotor and the stator winding *N* adapted to neutralize the armature reaction flux *R*, is connected to one phase of a two-phase supply while the stator field winding is connected to the other, and produces the motor field *F*. Because of the leakage fluxes linked with the armature circuit, the armature current lags, at starting, behind the e.m.f. of phase 1, and is therefore not quite in phase with the motor flux due to the e.m.f. of phase 2. The torque per ampere is good, the power factor fair. No phenomena occur under speed to materially change either the torque per ampere or the power factor. The speed of the machine is fairly constant. The weight efficiency is much greater than that of Fig. 26. Much better results can be obtained, particularly under speed, by adjusting the phase of the exciting e.m.f. relatively to that of the working e.m.f. The energy drawn from the phase feeding the armature, varies with the load; that drawn from the other is small and constant.

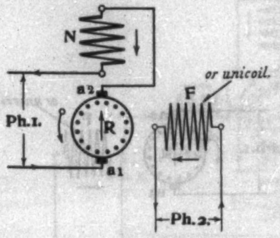

FIG. 27—(SEPARATELY-EXCITED) NEUTRALIZED SINGLE-PHASE SHUNT (CONDUCTION) MOTOR (WITH STATOR-EXCITATION)

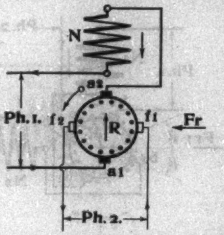

FIG. 28—(SEPARATELY-EXCITED) NEUTRALIZED SINGLE-PHASE SHUNT (CONDUCTION) MOTOR WITH ROTOR-EXCITATION

(Separately-Excited) *Neutralized Single-Phase Shunt* (Conduction) *Motor with Rotor-Excitation.* Fig. 28.

This only differs from the one shown in Fig. 27 in that the stator exciting winding F is dispensed with and the rotor winding along the horizontal axis used in its stead, the exciting e.m.f. being applied to the exciting brushes $f_1\, f_2$. The mode of operation and characteristics of the two machines are identical, except that a speed e.m.f. is generated at the exciting brushes by rotation in the vertical armature leakage flux, which so changes the phase of the resultant e.m.f. in the exciting circuit as to improve the power factor with increasing speed.

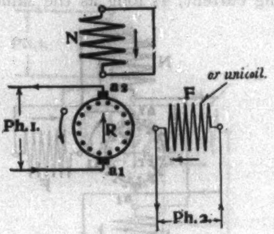

FIG. 29—(SEPARATELY-EXCITED) INDUCTIVELY-NEUTRALIZED SINGLE-PHASE SHUNT (CONDUCTION) MOTOR (WITH STATOR EXCITATION)

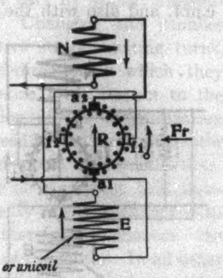

FIG. 30—SELF-EXCITED SINGLE-PHASE SHUNT (CONDUCTION) MOTOR (WITH ROTOR-EXCITATION)

(Separately-Excited) *Inductively-Neutralized Single-Phase Shunt* (Conduction) *Motor* (with Stator-Excitation). Fig. 29.

This differs from the motor shown in Fig. 27 in that the armature reaction flux R is neutralized inductively instead of conductively. The presence, in the vertical rotor axis, of the flux of mutual induction, which conveys the energy from the rotor to N, does not modify the mode of operation or the characteristics of the machine except as to commutation, because the speed e.m.f. generated in the rotor by its rotation in said flux appears along the horizontal rotor axis and is therefore ineffective.

Self-Excited Single-Phase Shunt (Conduction) *Motor* (with Rotor-Excitation). Fig. 30.

The armature circuit comprises the rotor winding along the vertical axis connected in series relation with the neutralizing winding N by way of the working brushes a_1 a_2. The armature reaction flux R is neutralized by N, leaving nothing but leakage fluxes in the vertical axis. The rotor is short circuited along the horizontal axis by means of the field brushes f_1 f_2 to form the exciting or motor field producing circuit. The stator winding E is connected across the mains and produces, in the vertical axis, a flux lagging 90 degrees behind the line or working e.m.f. By rotation of the rotor conductors in the flux E, an e.m.f. in phase with said flux is generated at the brushes f_1 f_2 and produces, along the horizontal rotor axis, a flux Fr lagging 90 degrees behind said e.m.f. and therefore in phase with the line e.m.f. and also with the working current, as long as the same is in phase with the working e.m.f. The flux E does not react on the working circuit because any e.m.f. it induces in the vertical rotor axis is equalled and opposed by the e.m.f. it induces in N. This machine will not start from rest, but is self-compensating, operates well at a constant speed and its speed is readily adjustable.

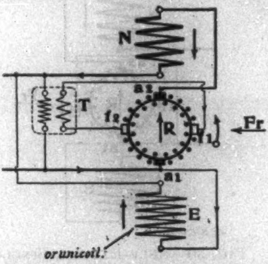

FIG. 31—COMPENSATED SELF-EXCITED SINGLE-PHASE SHUNT (CONDUCTION) MOTOR (WITH ROTOR-EXCITATION)

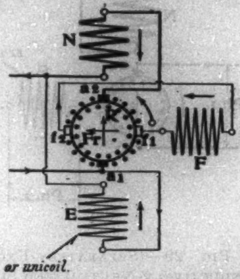

FIG. 32—SELF-EXCITED SINGLE-PHASE SHUNT (CONDUCTION) MOTOR WITH ROTOR AND STATOR-EXCITATION

Compensated Self-Excited Single-Phase Shunt (Conduction) *Motor* (with Rotor-Excitation). Fig. 31.

This differs from the previous motor only in that an e.m.f. differing in phase from the one directly responsible for the motor field and generated in the rotor by rotation, is introduced into the rotor exciting circuits for the purpose of adjusting the power factor of the machine by adjusting the phase of the resultant e.m.f. in the rotor exciting circuit. The compensating e.m.f. is in this case derived from the mains and is therefore in phase quadrature with the rotor exciting e.m.f.

Self-Excited Single-Phase Shunt (Conduction) *Motor with Rotor and Stator-Excitation.* Fig. 32.

This differs from the motor shown in Fig. 30 in that the rotor exciting brushes are not short-circuited but closed over a coaxial winding *F* located on the stator. The exciting e.m.f. generated in the rotor by rotation in the auxiliary or teaser flux *E*, sends a magnetizing current through *F*, as well as through the rotor along the horizontal axis, with the result that the motor field is produced in part by rotor, and in part by stator, ampere-turns. Changing the number of active stator exciting turns, or the direction in which they magnetize with respect to the direction of the magnetization produced by the horizontal rotor ampere-turns, changes the magnitude of the motor field independently of the working e.m.f., and therefore influences the speed of the motor. In all other respects the mode of operation and the characteristics are the same as those of Fig. 30.

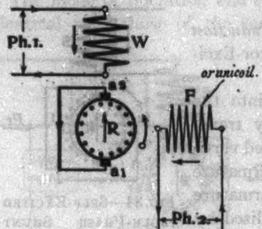

FIG. 33—(SEPARATELY-EXCITED) SINGLE-PHASE SHUNT INDUCTION MOTOR (WITH STATOR-EXCITATION)

(Separately-Excited) *Single-phase Shunt Induction Motor* (with Stator-Excitation). Fig. 33.

Working energy is inductively conveyed to the rotor from phase 1 along the vertical axis by means of a flux of mutual induction (transformer flux) due to a magnetizing current flowing through *W*. The ampere-turns due to the working current thus induced in the short circuited secondary (rotor) are equalled and opposed by corresponding ampere-turns in the primary *W*, set up by a primary working current derived from the mains. The rotor ampere-turns produce the armature reaction flux *R*, which is neutralized by the flux due to the primary working ampere-turns. The leakage flux along the vertical rotor axis is not neutralized, and the armature circuit is therefore not free from impedance. Exciting energy is conductively conveyed to the stator field winding *F* from phase 2, producing a motor field which is nearly in phase with the rotor or armature current and which cooperates therewith to produce the motor torque. In this as in all cases where a motor with one armature and one field axis per pole pair is fed from a two-phase supply, the load on the two phases is quite unequal, the one supplying the excitation being called upon to deliver only a small fraction of the energy required of the other. The machine has no self-compensating properties, and its speed is not constant under varying loads, mainly because of the rotor impedance due to the leakage field in the vertical rotor axis.

The power factor can be improved by suitably adjusting the phase of the motor field, but speed constancy is not secured thereby.

Self-excited Single-phase Shunt Induction Commutator Motor (with Rotor-Excitation). Fig. 34.

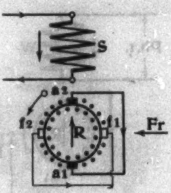

FIG. 34—SELF-EXCITED SINGLE-PHASE SHUNT INDUCTION COMMUTATOR MOTOR (WITH ROTOR EXCITATION)

Working energy is conveyed into the rotor along the vertical axis by transformer action from *S*. The induced vertical rotor ampere-turns do duty as armature ampere-turns, and produce the armature reaction flux *R*, which is neutralized by transformer action from *S*. The rotor leakage flux in the vertical axis is not neutralized. The working e.m.f. induced at the working brushes $a_1 a_2$ by the transformer flux, is of about the same phase as the line e.m.f. impressed on the stator winding *S*. The transformer flux lags 90 degrees behind the line e.m.f. The exciting e.m.f. is generated in the rotor by rotation of the rotor conductors in the transformer flux, and appears at the exciting brushes $f_1 f_2$. This speed e.m.f. is of same phase as the said flux, and therefore in phase quadrature with the line and with the rotor working e.m.fs. The motor flux *Fr* in the horizontal axis, is due to this exciting e.m.f., is in quadrature thereto, and therefore approximately in phase with the rotor ampere-turns in the vertical axis with which it cooperates to produce the motor torque. The back e.m.f. is generated in the vertical rotor axis by rotation in *Fr*. This machine is self-compensating, for another speed e.m.f. is produced at the exciting brushes by rotation of the rotor conductors in the vertical rotor leakage flux. This second speed e.m.f. so alters the phase of the resultant e.m.f. in the horizontal rotor axis, and therefore the phase of the horizontal flux, as to materially improve the power factor of the machine. This self-compensating feature cannot raise the power factor of this motor to anything like unity, but is sufficient to render an otherwise useless machine operative. The stator should not have any defined polar projections, and the winding *S* should be of the distributed type. This machine will not start from rest, but will run up to speed in any direction in which it is started. Its normal speed is the synchronous.

Compensated Self-Excited Single-Phase Shunt Induction Commutator Motor (with Rotor-Excitation). Fig. 35.

The mode of operation and characteristics of this motor are identical with those of the machine showing in Fig. 34, but auxiliary means are here added whereby the power factor of the machine can be adjusted at will. To this end an adjustable e.m.f., preferably in phase quadrature with the exciting speed e.m.f. generated in the rotor, is conductively introduced into the rotor exciting circuit. In this case this e.m.f. is derived from the mains by way of the transformer *T*. The normal speed of this machine is the synchronous; it is very constant under varying load. The power factor is under perfect control.

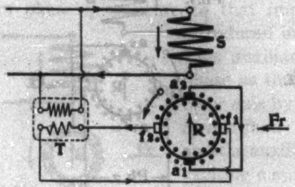

FIG. 35—COMPENSATED SELF-EXCITED SINGLE-PHASE SHUNT INDUCTION COMMUTATOR MOTOR (WITH ROTOR-EXCITATION)

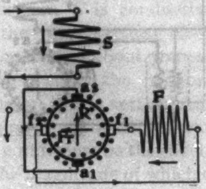

FIG. 36—SELF-EXCITED SINGLE-PHASE SHUNT INDUCTION COMMUTATOR) MOTOR WITH ROTOR AND STATOR-EXCITATION

Self-Excited Single-Phase Shunt Induction (Commutator) *Motor with Rotor and Stator-Excitation.* Fig. 36.

This differs from the motor shown in Fig. 34 in that the exciting brushes are not short-circuited but connected through a winding *F* located on the stator and in the horizontal or exciting axis. The exciting e.m.f. generated in the rotor by rotation in the vertical transformer flux sends a magnetizing current through *F*, as well as through the rotor along its horizontal axis, with the result that the motor field is produced in part by the rotor, and in part by the stator ampere-turns. Changing the number of active stator exciting turns, or the directions in which they magnetize with respect to the direction of the magnetization produced by the horizontal rotor ampere-turns, changes the magnitude of the motor field independently of the working e.m.f., and therefore changes the speed of the motor. This machine can run at speeds other than the synchronous, but in all other respects the mode of operation and the characteristics are the same as those of Fig. 34.

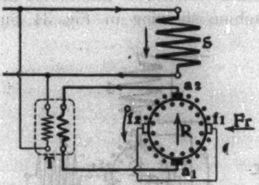

FIG. 37—SELF-EXCITED SINGLE-PHASE SHUNT INDUCTION-CONDUCTION (COMMUTATOR) MOTOR (WITH ROTOR-EXCITATION)

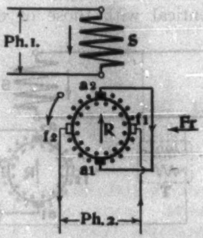

FIG. 38—SINGLE-PHASE SHUNT INDUCTION (COMMUTATOR) MOTOR WITH MIXED (ROTOR) EXCITATION

Self-Excited Single-Phase Shunt Induction-Conduction (Commutator) *Motor* (with Rotor-Excitation). Fig. 37.

In Fig. 34, the magnitude of the rotor working e.m.f. in the vertical axis and that of the rotor exciting e.m.f. in the horizontal axis, both depend on the magnitude of the vertical transformer flux. It follows that the magnitude of the working e.m.f. cannot be altered independently of the exciting e.m.f., by changing the magnitude of the transformer flux. In fact, any such change results in a proportional change in both e.m.fs. But an independent regulation of these two e.m.fs. is necessary if the speed of the machine is to be altered; the arrangement shown in Fig. 37 illustrates one way of achieving this result.

An e.m.f. of about the same phase as that of the line e.m.f. is conductively introduced into the working circuit of the rotor by means of the transformer *T* and the working brushes a_1 a_2.

The working e.m.f. induced in this circuit from S being also of about the same phase as that of the line e.m.f., the two will yield a resultant which will be of about the same phase as the induced working e.m.f., and either greater or smaller than it according to the direction of the conductively introduced component. This resultant will, of course, be the effective rotor working e.m.f. An adjustment of the magnitude of this resultant results in a change of the motor speed. This machine can run at constant speeds differing from the synchronous, but its mode of operation and characteristics are otherwise the same as those of the motor shown in Fig. 34.

Single-Phase Shunt Induction (Commutator) *Motor with Mixed* (Rotor) *Excitation.* Fig. 38.

This differs from the motor shown in Fig. 34 in that an e.m.f. in phase quadrature to that impressed on S is conductively introduced into the rotor exciting circuit. This auxiliary e.m.f. is of about the same phase as that generated in the horizontal rotor axis by rotation in the vertical transformer flux. The resultant of the generated and the auxiliary e.m.f. must be the effective exciting e.m.f., the magnitude of which can therefore be changed independently of the rotor working e.m.f., thus securing speed regulation. This machine will start from rest and can be run at constant speeds differing from the synchronous; in all other respects it is the same as that shown in Fig. 34.

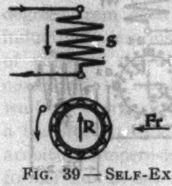

Fig. 39—Self-Excited Single-Phase Shunt Induction Motor (with Rotor-Excitation)

Self-Excited Single-Phase Shunt Induction Motor (with Rotor-Excitation). Fig. 39.

The mode of operation and characteristics of this machine are identical with those of the motor shown in Fig. 34. The stator winding S produces a vertical transformer flux which conveys the working energy into the rotor and is also responsible for the rotor exciting e.m.f., which is generated in the horizontal axis by rotation of the rotor conductors in this transformer field. The rotor working ampere-turns responsible for the armature reaction flux are neutralized by transformer action from S; their space distribution is shown by the dots and circles located inside the rotor circle in Fig. 34 and remains unaltered independently of the revolution of the rotor. The space distribution of the rotor exciting ampere-turns responsible for the motor torque producing field *Fr*, is as shown by the dots and circles located outside the rotor circle in Fig. 34 and also remains unaltered as long as the rotor revolves. The speed e.m.f. due to rotation of the rotor conductors in the vertical rotor leakage flux, acts to improve the power factor. The squirrel cage construction provides paths over which currents may close through any two rotor conductors, with the result that neither the intensity of the working nor that of the exciting current is the same in all the conductors. The machine will not start from rest, but if given a sufficient impulse in either direction will run up to its normal speed, which is very near the synchronous. Its working speed is practically constant under varying loads.

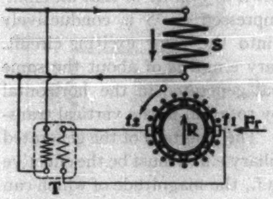

FIG. 40—COMPENSATED SELF-EXCITED SINGLE-PHASE SHUNT INDUCTION MOTOR (WITH ROTOR-EXCITATION)

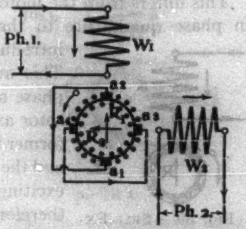

FIG. 41—TWO-PHASE SHUNT-INDUCTION COMMUTATOR MOTOR (WITH STATOR-EXCITATION)

The stator should not have any defined polar projections, and the stator winding should be distributed.

Compensated Self-Excited Single-Phase Shunt Induction Motor (with Rotor-Excitation). Fig. 40.

This differs from the previous motor in that the rotor carries a squirrel cage, a commuted winding and cooperating brushes located in the horizontal axis. An exciting speed e.m.f. is generated along the horizontal axis of both windings so that both will contribute equally to the production of *Fr* if the brushes f_1 f_2 are short circuited. If the e.m.f. per conductor of one of these windings is artificially raised, this winding will contribute more than one half of the total motor field ampere-turns, and if the increase has been of sufficient magnitude, it may even contribute all of the motor field ampere-turns, in which case there will be no current in the horizontal axis of the other winding. A further increase will cause a reverse current to flow in the other winding, for the tendency is to keep Fr constant. In Fig. 40 an auxiliary e.m.f. derived from the mains with the help of the transformer T is conductively introduced into the circuit of the commuted winding; its magnitude and phase are such that the burden of the motor field production is shifted to the commuted winding, and the phase of the motor field it produces, is adjusted to improve the power factor of the motor.

Two-Phase Shunt-Induction Commutator Motor (with *Stator-Excitation*). Fig. 41.

This machine really consists of two static transformers with primaries disposed on the stator and displaced by 90 electrical degrees from each other, and a common secondary rendered inductively responsive along the axis of each primary by means of pairs of short-circuited brushes. Each stator winding is connected to one phase of the supply, inductively conveys working energy into the rotor along its own axis by means of a transformer flux, and neutralizes, by transformer action, the armature ampere-turns it induces in its own axis. The transformer flux in one axis cooperates with the rotor ampere-turns in the other axis to produce one half of the motor torque; the other half being due to the interaction of the transformer flux in the second axis with the rotor ampere-turns in the first. Each transformer flux therefore also does duty as a motor field. Under speed, a back e.m.f. is generated in each rotor axis by rotation in the transformer flux at right angles to it. While the armature reaction fluxes R_1 R_2 are neutralized, yet the coaxial rotor leakage fluxes are not. By rotation of the rotor conductors in the vertical rotor leakage flux, a compensating e.m.f. is generated in the horizontal rotor axis, appears at the brushes a_3 a_4, and is of such a phase as to reduce the impedance of the horizontal axis. The impedance of the vertical rotor axis is similarly reduced by an e.m.f. appearing at the brushes a_1 a_2 and generated by rotation of the rotor conductors in the horizontal rotor leakage flux. The machine clearly has self-compensating properties, but the e.m.fs. in question cannot reach a value sufficient to raise the power factor to unity. The normal speed of the machine is very near the synchronous.

Compensated Two-Phase Shunt Induction Commutator Motor (with Stator-Excitation). Fig. 42.

This motor differs from the foregoing in that an auxiliary e.m.f. in quadrature with the induced working e.m.f. is conductively introduced into each of the rotor working or armature circuits by means of the transformers T_1 and T_2. The direction of each auxiliary e.m.f. is chosen to reduce the impedance of the rotor axis to which it is applied. The power factor of the machine can be adjusted by adjusting these *compensating* e.m.fs.

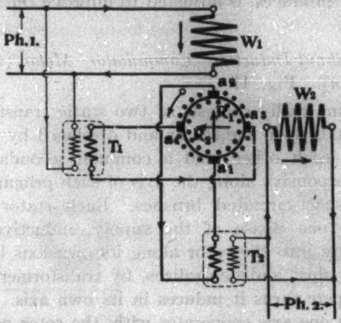

FIG. 42—COMPENSATED TWO-PHASE SHUNT INDUCTION COMMUTATOR MOTOR (WITH STATOR-EXCITATION)

Two-Phase Shunt Induction-Conduction (Commutator) *Motor* (with Stator-Excitation). Fig. 43.

This differs from the foregoing motor in that an auxiliary e.m.f. in phase with the induced working e.m.f. is conductively introduced into each of the rotor working circuits by means of the transformers T_1 and T_2. By this means the effective working e.m.f. in each rotor axis can be adjusted independently of the transformer fluxes and the speed of the machine made to differ from the synchronous. These *speed-regulating* e.m.fs. should, of course, either assist the induced working e.m.fs. in both axes or oppose them in both.

Two-Phase Shunt Induction Motor (with Stator-Excitation) Fig. 44.

This machine is the squirrel cage equivalent of the commutator motor shown in Fig. 41, and stands in the same relation to it as does Fig. 39 to Fig. 34.

Compensated Two-Phase Shunt Induction Motor (with Stator-Excitation). Fig. 45.

This is a combination of the compensated commutator motor of Fig. 42 with the squirrel cage motor of Fig. 44. The transformer in each axis has two secondaries with differing impedances, that of the squirrel cage is adjusted automatically and is beyond the control of the operator, that of the commuted winding is under control. The current in the first can never lead the working e.m.f. impressed on it. The current in the second can be made to lead the working e.m.f. impressed on the commuted winding. The secondary with the lower impedance, *i.e.*, with the commuted winding, will carry the greater number of ampere-turns. Unity or leading power factor can only be obtained by causing the current in each axis of the commuted winding to lead the induced working e.m.f. in that axis. The stator windings in all these machines should be distributed, and the stator should have no defined polar projections.

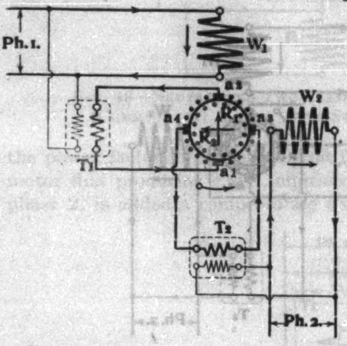

FIG. 43—TWO-PHASE SHUNT INDUCTION-CONDUCTION (COMMUTATOR) MOTOR (WITH STATOR-EXCITATION)

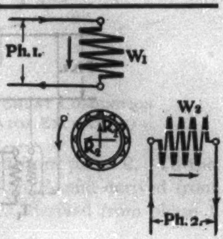

FIG. 44 — TWO-PHASE SHUNT INDUCTION MOTOR (WITH STATOR-EXCITATION)

Neutralized Two-Phase Shunt Conduction (Commutator) *Motor* (with Stator-Excitation). Fig. 46.

Working energy is conductively conveyed to the rotor from phase 1 along one axis, and from phase 2 along an axis displaced by 90 electrical degrees from the first. The rotor ampere-turns, or the reaction fluxes R_1 R_2 thus set up in each axis, are conductively neutralized by means of the stator windings N_1 and N_2. The motor field winding F_1 located coaxially with the rotor circuit connnected to phase 1, is fed from phase 1. The motor field winding F_2 displaced by 90 electrical degrees from F_1, is fed from phase 2. The motor flux set up by the field winding connected across one phase cooperates to produce one half the motor torque with the rotor ampere-turns produced by the other phase, and *vice versa.* Rotation of the rotor conductors in the rotor leakage flux in one axis generates in the other a speed e.m.f. which reduces the impedance of the working circuit of this other axis, and *vice versa.* Since working and exciting currents are independent of each other, the machine must have a shunt characteristic. This motor is not self-compensating. Armature and field circuits being quite independent, the speed of this machine can be set to any desired value. No defined polar projections should be used, and the neutralizing windings should be distributed so as to follow the distribution of the ampere-turns in the corresponding rotor axis.

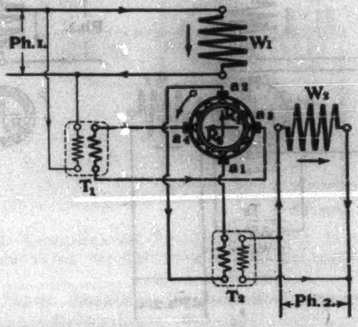

Fig. 45—Compensated Two-Phase Shunt Induction Motor (with Stator-Excitation)

Neutralized and Compensated Two-Phase Shunt Conduction (Commutator) *Motor* (with Stator-Excitation). Fig. 47.

This motor differs from the foregoing one in that two e.m.fs. are impressed on each of the field windings F_1 and F_2. To the motor flux producing e.m.f. impressed on F_1 and derived from phase 1, is added a compensating e.m.f. derived from phase 2 by means of the transformer T_2 and adjusted to improve the power factor in the rotor circuit fed from phase 2. To the motor flux producing e.m.f. impressed on F_2 and derived from phase 2, is added a compensating e.m.f. derived from phase 1 by way of the transformer T_1 and adjusted to improve the power factor in the rotor circuit fed from phase 1. In all other respects this machine is identical with that shown in Fig. 46.

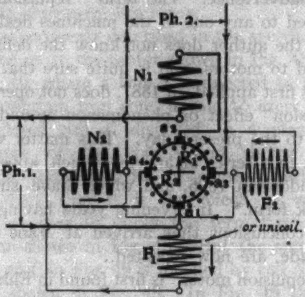
Ph. 2.
N1
N2
a2
a4
a3
a1
R1
R2
Ph. 1.
F2
or unicoil.
F1

Fig. 46—Neutralized Two-Phase Shunt Conduction (Commutator) Motor (with Stator Excitation)

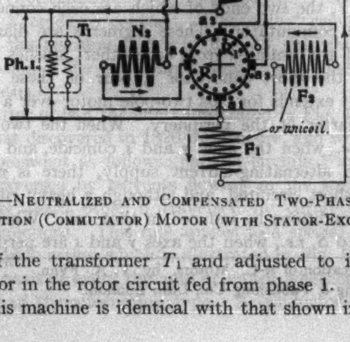
Ph. 2.
T2
N1
T1
N2
a2
a4
a3
a1
R1
R2
Ph. 1.
F2
or unicoil.
F1

Fig. 47—Neutralized and Compensated Two-Phase Shunt Conduction (Commutator) Motor (with Stator-Excitation)

REMARKS

It is believed that all the principal forms of alternating-current motors have been classified; if any have been omitted, it is due to inadvertence. The term "repulsion motor" has not been applied to any one of the machines dealt with. The reason is that the author does not know the definition of this term as applied to motors. and is quite sure that the machine to which it was first applied, in 1887, does not operate by virtue of any "repulsion" effect or phenomenon as understood from the year 1820 to the present day. This matter was discussed at some length in a series of articles which appeared in *The Electrican* (London) in 1906, and which have since been reprinted in book form.* Intervening years having only served to confirm the conclusions then arrived at, some of the statements then made, are now repeated.

The term "repulsion motor" is first found in Elihu Thomson's U. S. Patent No. 363,185 of 1887. The form of Thomson's motor as described and illustrated in that specification, is shown in Fig. 48. Within the stationary coil *S* is mounted a pivoted coil *Y*, the two ends of which are each connected to a segment of a commutator. These segments are diametrically disposed, and are insulated from each other; brushes *b b* short-circuited by the short conductor *r*, bear on these segments. Each segment extends for this two-pole motor over a little less than one quarter of the periphery. When the two coils are concentric, *i.e.*, when the axes *y* and *s* coincide, and *S* is connected to an alternating-current supply, there is no torque even if *Y* is short circuited, and although a heavy current will under such conditions be induced in that coil. When *Y* is at right angles to *S*, *i.e.*, when the axes *y* and *s* are perpendicular

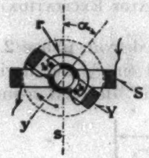

FIG. 48

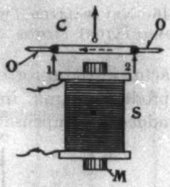

FIG. 49

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*The Classification of A-C. Motors, by V. A. Fynn. "The Electrician" Printing & Publishing Co., Ltd., London.

to each other, there is no torque and no current in *Y* even if short-circuited. In the intermediate positions, *i.e.*, for any values of α between 0 and 90 degrees, a torque will be exerted in the direction shown by the arrow.

Among the experiments described in the specification referred to as having led up to the motor shown in Fig. 48, is that illustrated in Fig. 49, where a coil *S*, connected to an alternating supply and having an iron core, is said to exert a "repelling" effect on a closed coil *C* disposed in a plane parallel to the convolutions of the coil *S* and shown in section in Fig. 49. This statement is, of course, perfectly correct, and it is evident that it is the effect to which it refers that led the inventor to apply the term "repulsion motor" to the machine shown in Fig. 48. But the special conditions under which coil *C* in Fig. 49 is repelled by coil *S* do not obtain in the motor shown in Fig. 48. In Fig. 49 the "repelling" effect exerted on coil *C* is of the same direction and magnitude all along the circumference of the coil, as indicated by the small arrows 1 and 2, with the result that coil *C* will move away from coil *S while keeping parallel to it.* If coil *C* were pivoted on an axis *O* passing through its center, and parallel to the convolutions of *S*, there would be absolutely no tendency for that coil to rotate, but the "repulsion" effect would tend to bend the shaft and the coil. When in Fig. 48 the convolutions of coil *Y* are parallel to those of *S*, that is, when the axes *y* and *s* coincide—reproducing in this figure as nearly as they can be reproduced, the conditions obtaining in figure 49—then there is and can be no rotation between coils *Y* and *S*, but *there is* "repulsion" between the two, owing to which, coil *S* tends to expand while coil *Y* tends to contract. The only "repulsion" effect present in the machine shown in Fig. 48, contributes nothing to the rotation of the free member and merely tends to destroy the apparatus.

As a matter of fact the effect illustrated in Fig. 49 is nothing else but that discovered in 1820 by Ampere, and which he summed up somewhat as follows: parallel circuits "attract" each other if traversed by currents flowing in the same direction, and "repel" each other if traversed by currents flowing in opposite directions. This rule applies to a special case of that electrodynamic action which is illustrated in Fig. 50 and which forms the basis of every dynamo or motor whether of the continuous or of the alternating type. A conductor, *A*, through which a current flows, for instance, upwards through the paper, as indicated by dot, when immersed in a field *F* directed from top to bottom of the paper, will tend to move to the right. Ampere's rule is illustrated in Figs. 51 and 52, which show respectively the "attraction" and the "repulsion" of parallel circuits. The rule illustrated in Fig. 50, when applied to Figs. 51 and 52, explains this behavior, it being only necessary to remember that if in Fig. 50 the direction of the current through *A* or the direction of the field *F* is changed, then the direction of the torque exerted on *A* will be reversed. Taking Fig. 52 we have the current in conductor *A* producing a field of the direction indicated by the full concentric lines, these lines cut conductor *B*, and according to Fig. 50 this conductor *B* will move to the right; similarly the field produced by *B* (dotted lines) acting on *A* will cause the latter to move to the left, hence the "repulsion." Ampere very correctly restricted his rule to *parallel circuits*, and the author can see no reason for altering this now, by describing as "repulsion" the effect responsible for the operation of a particular type of single-phase motor in which there are no interacting parallel circuits.

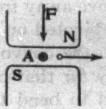

FIG. 50

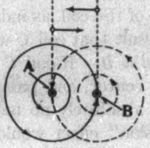

FIG. 51

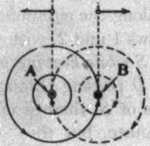

FIG. 52

Of course Ampere's rule holds good for alternating currents as well as for continuous currents; in the former case, however, the magnitude of the "repulsion" or "attraction" also depends on the relative phase of the currents in the two conductors, just as the torque exerted on *A* in the more general case of Fig. 50 also depends on the relative phase relation between the field *F* and the current in *A*. One true example of the application of Ampere's "repulsion" effect in alternating-current practise is to be found in the constant-current transformer with movable secondary coil, one form of which is shown in Fig. 49. In this figure, one component of the current in coil *S* goes to excite the field *M* which conveys the secondary current into coil *Y* by induction; the other component is equal and opposed to that secondary current. The secondary current in Y and the component in S neutralizing the effect of that secondary current, are of opposite phase, which is equivalent to the same phase but opposite direction, and are responsible for the major part of the "repulsion" effect.

The operation of the motor in Fig. 48, like that of any other electrodynamic motor, is due to the electrodynamic action illustrated in Fig. 50, but not to the special case of same discovered and characterized by Ampere.

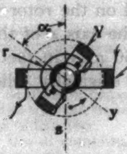

FIG. 53

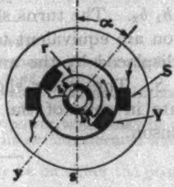

FIG. 54

Returning to the consideration of Thomson's original motor, shown in Fig. 48, it is clear that its operation will not be altered in principle, if the brushes are displaced in the manner shown in Fig. 53; the direction of rotation will, however, be reversed. The principle of operation will also remain the same if the coils S and Y are embedded in laminations, as shown in Fig. 54. Nor will the principle be changed if the single coil Y is replaced by a continuous commuted winding such as shown in Fig. 55, individual coils of which are short-circuited by means of the independent brushes b_1 b_2. Fig. 55 shows what may be described as the modern form of rotor for the original Elihu Thomson motor. Figure 56 only differs from Fig. 55 in that the two brushes

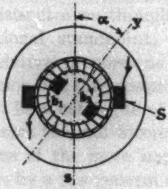

FIG. 55

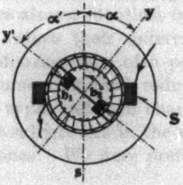

FIG. 56

b_1 b_2 are also interconnected outside of the rotor winding. The brushes of this machine, which is described in U. S. Patent No. 389,352 of 1888, short-circuit individual coils of the commuted winding on the rotor in exactly the manner shown in the Thomson motor of Fig. 55, but the machine nevertheless revolves in the *opposite* direction, for the reason that a greater and opposite torque is produced by the rest of the commuted winding which is short circuited by the external interconnection between the brushes b_1 b_2. The turns short-circuited by this external interconnection are equivalent to a single coil on the rotor with the axis y' displaced by the angle α' from the axis s of the stator winding S. The motor shown in Fig. 56 may in fact be said to operate in spite of the arrangement originally relied upon by Thomson.

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THE CLASSIFICATION OF ELECTROMAGNETIC MACHINERY

BY F. CREEDY

ABSTRACT OF PAPER

The author proposes to classify all dynamo-electric machinery according to five sets of characteristics, as follows:

1. Type of field, as constant intensity, variable intensity, multiple polarity and homopolar.
2. Method of disposal of secondary power, which may be zero, wattless, utilized in separate apparatus or transformed and returned to the line.
3. Use of commutators, which may be on either the primary or the secondary, or may be absent.
4. Method of magnetization, namely, high-frequency magnetization as in the ordinary induction motor and low-frequency magnetization as in synchronous and compensated motors.
5. Method of connection. Many types may be connected either in series or shunt. A tabulation of these characteristics is given, by reference to which any dynamo-electric machine can be classified.

THE FOLLOWING paper is an attempt to arrive at a natural classification of the electromagnetic machine. One of the principal uses of such a classification is to bring out the common points of different types which are usually regarded as totally distinct even though they are almost identical from the constructional standpoint, and to reduce their differences to proper relative proportions. The disadvantage of a paper on classification like the present is, of course, that one is reduced to a somewhat bare catalogue of possible types and their characteristics, whereas the real interest of the subject lies in the detailed description of the more important ones. We may preface our discussion by a few general remarks.

1. No discussion will be attempted of homopolar machines, which form a class entirely apart from all others.

2. While almost all the machines described may be used as generator or motor, they will in practise be used only as motors, since the requirements of a generator are so uniform that there is no scope for a large variety of types, while the infinite variety of industrial work gives rise to a corresponding variety of types of motor. In generators the tendency is to uniformity

and in motors to variety, and hence our subject might almost as well be called " The Classification of Electric Motors."

3. For a similar reason, viz., the powerful tendency towards standardization, and the necessity for one system of distribution catering to a vast variety of applications, together with the urgent necessity of economy due to the great length of transmission lines, we may dismiss from our minds the likelihood of new and more complicated systems of transmission arising, although several such are imaginable, and confine our attention to machines operating from standard direct-current, single or polyphase systems.

4. Of the two distinct constructional forms in use, viz., the type having uniformly slotted stator and rotor and a constant air gap all round, and the salient pole type, we shall consider the former as universal and ordinary, and the latter as a special case applicable to certain types only.

5. In all the discussions below, unless a statement to the contrary is made, we shall treat our machines as " ideal", *i. e.* entirely devoid of all losses and leakages.

6. Theories come and go, while the machines we wish to classify remain the same. Our methods of classifications should be of a fundamental nature and should not owe their validity to the acceptance of a particular theory, nor should they be unintelligible to those who have not gone through a particular course of study. They should be based either on constructional features, where these can be proved to have a general significance and not to be accidental, or on mechanical considerations in connection with torque, power and energy. These considerations apply to nomenclature also, and should render us very conservative in inventing new names for old apparatus.

A well understood name, even though based on an obsolete theory is usually better than a new name based on a theory which may become obsolete in its turn.

Having cleared the ground by the above considerations we may proceed to our main subject.

We shall regard the induction machine or " general alternating-current transformer," as Steinmetz calls it, as fundamental, and shall proceed to derive all other types from it.

Our general dynamo electric machine, then, consists of two concentric magnetic elements, separated by an air gap, and capable of relative rotation. Each of these elements bears a number of conductors disposed next the air-gap in slots parallel to the shaft. The conductors of one or both elements are interconnected in such a way as to give rise to a definite number of poles, conductors being led off from the stationary element direct to the line, save in a few cases where it is short-circuited. The rotor may be of three distinct types (a) short-circuited, (b) fitted with collector rings, (c) fitted with commutator. Every type of dynamo-electric machine whatsoever, with the exception mentioned above, may be built in a form covered by the above description and the differences between different types consist merely of differences in the method of connection to the line and of connection between rotor and stator.

We have next to classify these types of connection and show why they are required. In order to do this we must first consider our electric system as a machine. From the mechanical point of view then, the generator is a gearing which transmits the motion of the prime mover to the polyphase line, changing the power given out by the prime mover from the mechanical form to that of a rotary system of electrical stresses revolving at a definite speed, say of 25 or 60 cycles (or revolutions) per second. The polyphase line we may compare to a mechanical line shaft transmitting the power to a distance and the motor to another gearing, retransforming the power into a mechanical torque operating at a certain speed.

What will this speed be? To determine this, consider the following relation which it is well known exists between the speed and primary and secondary frequencies of the induction machine. Speed (rev. per sec.) × no. of pole pairs = difference between primary and secondary frequencies (cycles per sec.), or mechanical speed of rotor equals speed of wave relative to stator, minus speed of wave relative to rotor,

or
$$S = W\,(f_1 - f_2) \tag{1}$$

where W is twice the polar pitch.

These equations show that we cannot tell the mechanical speed of the rotor unless we know the rotor as well as the stator frequency. Multiplying both sides of this equation by the torque we get T multiplied by mechanical speed equals T multiplied by speed of wave relative to stator minus T multiplied by speed of wave relative to rotor; or, mechanical output equals primary electrical input minus secondary electrical output. **(2)**

This equation shows that besides the mechanical power and the electrical input into the primary, there is a certain amount of power generated in the secondary proportional to the secondary frequency. The above simple considerations bring us to our first principle of classification. It has been emphasized above that the motor is a device for changing electrical power incoming from the line into mechanical power, and hence the existence of this secondary power raises a serious problem—what to do with it. We shall classify our machines first according to means adopted for disposing of the secondary power. A substantially identical principle for adjustable-speed motors may be deduced from the equation (**1**) above.

·This equation shows that the speed can only vary

1. If the primary frequency varies,
2. If the secondary frequency varies,
3. If the number of poles varies,

and we may classify adjustable speed motors according to which of these means is adopted to vary the speed. Before proceeding further we shall develop a mechanical analogy between our induction machines and certain types of epicyclic or differential gears which is capable of being carried into considerable detail, and throws a great deal of light on the real nature of many arrangements of machines. This analogy enables us to abstract entirely from the electrical features of the problem and consider power and torque alone. We shall show also, that if we compare the relative speed of the two elements of our machine to the speed in revolutions per second of one shaft of a differential gear, and the frequencies in the two members to the speed of the other two shafts, the above relation between speed and frequencies corresponds to that between the speeds of the three independent shafts of the differential gear. Such a gear is shown in Fig. 1.

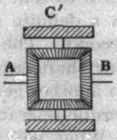

FIG. 1

If the shafts A, B and C' go at speeds of A rev. per sec., B rev. per sec., and C' rev. per sec. respectively, it is well known that C' will be the mean of A and B, or $C' = \frac{1}{2}(A + B)$.

If therefore, we gear another shaft C to the shaft C' so that the speed of C is twice that of C', or $C' = \frac{1}{2}C$, we shall have

$$\begin{aligned} C &= A + B \\ B &= C - A \\ A &= C - B \end{aligned}$$

Or, in order to introduce a constant, corresponding to the "number of pole pairs" in the electric machine, we may suppose B or A geared to another shaft by gearing of any desired velocity ratio.

The point of particular interest to us about this gear is the fact that the equation regulating the speeds contains three potentially independent variables, so that it is necessary to know two of them before we can determine the third. For instance, if we know A we cannot find B unless we also know C. In the electric case, if we know the primary frequency of an induction motor, for instance, we cannot tell the speed, until we know the secondary frequency also. It will be useful to develop the analogy between a differential gear and an induction motor somewhat further. Let us put:

Primary frequency $= A =$ speed of driver shaft of differential.

Mechanical speed $= B =$ speed of driven shaft of differential.

Secondary frequency $= C =$ speed of intermediate shaft of differential.

We then have: $B = C - A$ in both cases, if we suppose our induction motor has two poles.

So long as C, the intermediate speed or secondary frequency, remains unsettled, we cannot tell what B will be.

We may take a number of suppositions relating to these which are tabulated below:

ELECTRIC CASE	MECHANICAL CASE.
Secondary open-circuited. Machine can deliver no torque, but can run at any speed without opposition, if driven.	*Shaft C free.* B can deliver no torque, but can run at any speed without opposition if driven.
Secondary short-circuited through zero resistance. Machine can run at same speed as A and deliver same amount of power as flows into primary.	*C. Fixed.* B runs at the same speed as A, and delivers same amount of power taken in at A.
Secondary, neither open nor short-cuited but closed through a fixed resistance R there being no secondary leakage.	*C. neither fixed nor free but its power output consumed by a brake giving a torque proportional to the speed at which it is driven and consuming power therefore proportional to the square of the speed.*
Torque is proportional to the secondary current, which is equal to the secondary e.m.f., divided by the resistance. Secondary e.m.f. and, therefore current is proportional to second-	The torque of each of the three shafts must be equal, for multiply the equation $B = C - A$ by the torque T_0 required by the load, and we get: $T_0 B = T_0 C - T_0 A$. This equation can only be con-

ELECTRIC CASE

ary frequency, or say $T_0 = K\,C$ as in the Mechanical case.

Thus we get $B = \frac{T_0}{K} - A$, exactly the same torque speed characteristic as in the mechanical case.

MECHANICAL CASE

sistent with the conservation of energy, if T_0 is also the torque of the other two shafts.

In this case:

$T_0\,B$ = Output of driven shaft.

$T_0\,C$ = Output of intermediate shaft.

$T_0\,A$ = Input of driver and the equation becomes true.

If we now put:

Torque of intermediate—$T_0 = K\,C$ in accordance with the above assumption, we clearly determine the speeds of all three shafts, for we now have

$$B = \frac{T_0}{K} - A$$

This is the torque speed characteristic of our gear.

According to this analogy, therefore, we may compare any electric machine having a simple harmonic wave of flux to a differential gear, the primary input corresponding to the input of the driver shaft, the mechanical output corresponding to the output of the driven shaft, and the secondary output corresponding to the output of the intermediate shaft.

Hence a set consisting of motor and generator may be compared to two such differential gears coupled together.

Now it is well known that no combination of gearing, however arranged can give us a smooth and gradual speed change, the uttermost possible being a number of steps. Yet certain electric machines do give this gradual speed change, since they embody a device which we have not yet discussed, viz: a commutator. The commutator may be regarded as the only practical gradually adjustable gear in existence.

Consider a commutator fitted with a polyphase arrangement of brushes as in Fig. 2. If polyphase currents of frequency f_1 cycles per sec. are fed in through the terminals $A_1\ A_2\ A_3$ and the commutator revolves with speed S revolutions per sec. the slip rings $B_1\ B_2\ B_3$ which are supposed to be equal in number to the commutator segments, and one being joined to each, will deliver polyphase currents of frequency $f_2 = f_1 \pm S$ according to whether the commutator revolves with or against the direction of rotation of the inflowing current.

Hence for the case of a "two-pole" arrangement of the brushes on the commutator, we have

$$S = \pm (f_1 - f_2)$$

This is particularly obvious if $f_1 = 0$. If, however, the brushes are connected "four-pole" for instance as shown in Fig. 3, so that the slip ring which is connected to a certain segment say, goes through a complete cycle while the commutator turns through 180 deg. instead of 360 deg., the difference between the commutator and slip ring frequencies will be twice as great as before, or $2S = \pm (f_1 - f_2)$.

In general if $\frac{P}{2}$ be the number of pole pairs for which the commutator brushes are joined

$$s \times \frac{P}{2} = \pm (f_1 - f_2)$$

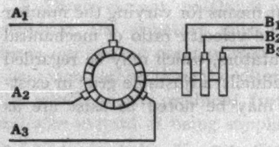

FIG. 2

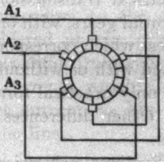

FIG. 3

exactly the same equation as we had for the induction machine. For a two-pole machine $\frac{P}{2} = 1$ and for a four-pole machine $\frac{P}{2} = 2$.

In the commutator frequency converter the whole of the power flowing into the commutator flows out of the slip rings, notwithstanding any change of frequency, whereas, in the electric machine, the power flowing into the primary divides into two parts, one part proportional to S appearing in mechanical form and the other proportional to f_2 appearing as electrical power in the secondary. From considerations of power, this is the outstanding difference between the two cases.

We may now summarize the results we have already obtained:

(1) That motor and generator form together with the transmission line a mechanism in the ordinary sense of the word; that is, a means of modifying motion and force, or in more general language, of changing the flow of energy.

(2) That the electrical and mechanical speed-torque characteristics of the machine are those of a differential gear, there being a definite relation, $S \times \frac{P}{2} = (f_1 - f_2)$ between the stator and rotor frequency and the mechanical speed which is identical with that in a differential gear. The relation between the mechanical and electrical speeds s, f_1 and f_2, can only be changed by changing the number of poles.

(3) the primary function of the commutator is that of a frequency changer which can change frequencies arbitrarily without change of voltage or power.

(4) The same equation, $S \times \frac{P}{2} = f_1 - f_2$, is also characteristic of the commutator which is a purely electrical differential gear inherently incapable of transmitting a torque.

Hence the different types of electrical machine and systems of electrical transmission may be compared with a number of differential gears, with or without means for varying the number of poles, which corresponds to the velocity ratio of mechanical gear and with or without commutators, which may be regarded as the only practical form at gradually adjustable gear in existence. Other differences which may be noted to exist are as follows:

(5) Systems otherwise identical differ in their method of magnetization.

(6) Several revolving fields may be superposed in the same structure as in the Hunt "internal cascade" machine, the single-phase or elliptic-field machine, or the split-pole converter. Thus the above considerations give us three principles of classification.

(1) According to the disposition we make of the secondary power output or output from the "intermediate shaft" of the differential gear. A parallel principle leading to approximately the same result is according to which of the quantities P, f_1, or f_2, is regarded as variable in adjustable speed machines.

(2) According to the manner in which we employ the commutator in our system.

(3) According to the method of magnetization. In addition to this, the machines may be either generators, motors, converters, double current generators, phase advancers, etc., but this really introduces no new feature, as most machines

are capable of all or most of these functions. If our classification is exhaustive we shall find that when we have assigned our machines a place in each of our classes it is completely defined and nothing further remains to be specified, apart from constructional details. We shall avoid circumlocution if we define the primary as the element into which power flows from the line.

First Principle. Methods of disposing of the secondary power.

The secondary power may be made zero by making the secondary frequency zero or as low as practicable. This is done in almost all the standard types of machine in wide commercial use. Examples of this are the following:

1. Ordinary synchronous machines of all kinds where the secondary frequency is made exactly zero.

2. Induction machines with short-circuited rotor where the secondary frequency is made very low, and the small amount of secondary power generated is dissipated as heat.

3. Direct-current machines where according to the above definition the armature must be considered as the primary. From our present point of view they only differ from synchronous machines in that the alternating currents which flow in the windings are produced from direct current by the commutator instead of being supplied by the line.

4. Repulsion machines (ordinary and inverted) and in fact all types in which all the windings on one member are short-circuited. How the secondary power in elliptic field machines may be reduced to zero without confining the machine to synchronous speed will be shown below.

Secondary power may be entirely wattless, as in the single-phase series machine.

Secondary power used in another apparatus (*cascade systems*). In this case the power flowing out of the secondary is supplied to a second machine which is either independent or mechanically coupled to the first. Examples of this are induction machines cascaded with other induction machines, synchronous machines, or a-c. commutator machines.

Secondary power transformed to primary frequency by a commutator and returned to the line. Examples of this are certain types of a.c. commutator machines when running at speeds differing from synchronism.

Second Principle. According to the manner of using the commutator.

If we confine ourselves, as we are doing, to a single machine, the only two possible methods of using a commutator are:

(1) On the primary as in the d-c. machine.

(2) On the secondary as in the a-c. commutator machines mentioned above. If, however, as may readily be done, we extend our survey to groups of machines working in conjunction as in cascade sets for instance, a large variety of further interesting methods of application are revealed. A third way of applying it, however, is to confine currents to a definite axis in space as in the repulsion motor etc. This method only applies to elliptic field machines.

Third Principle. Methods of magnetization.

Two distinct methods of magnetization may be distinguished.

1. The primary may be the seat of the magnetizing currents which may be led in direct from the line as in the normal induction machine and several others. This may be called high-frequency magnetization and involves the appearance of a considerable amount of reactive power proportional to the frequency in the line circuit.

2. The secondary may be the seat of the magnetizing currents which may be led in direct from the line through a frequency changing commutator or supplied by an exciter. This latter method may be called low-frequency magnetization and does not give rise to reactive power in the line. In order to understand the various methods of magnetization better we shall devote further space to the matter later on.

CIRCULAR OR CONSTANT INTENSITY FIELD MACHINES

To make up a complete circular-field dynamo electric machine we have four elements: the line, the stator, the rotor, and the commutator. By making various combinations of these we obtain different types of machine having different characteristics and adapted to different purposes. Different types of winding exist, each capable of being adapted for connection to direct current, single, or polyphase lines or to a commutator. Each of these is capable of being built for many different polarities. Hence when we say "connect the line to the primary" we therefore assume that it is provided with an appropriate winding. In the following table are shown the various permutations, etc., of the four elements mentioned above which will give rise to practical machines. It will be seen that there is not a very great number.

1. *The Induction Machine.* The simplest is that in which the commutator is entirely absent and the secondary short-circuited, the primary being connected to the single- or polyphase line and being wound in a suitable manner. In this case the secondary power is very small, being absorbed entirely by the secondary resistance, while the commutator is absent, and the primary winding has two distinct functions to perform, viz., magnetization and the production of a torque. For the former purpose we require a distribution of current density in the stator slots which is in quadrature with the wave of flux density, assumed to be harmonic when we assume a circular field. For the latter purpose the distribution of current density in the stator slots should be in phase with the wave of flux density. Hence two currents, the "magnetizing" and "load" currents, in quadrature with one another, must flow in the stator winding, and this must be of the distributed type in order to allow of its producing an approximate sine wave of magnetism. Such a machine is confined to speeds close to synchronous.

2. *The Synchronous Machine.* The two distinct functions which the stator winding performs in the above machine are separated in the next type which differs from the above solely in that the magnetization is of the low-frequency type and therefore the magnetizing currents on the secondary. Although a distributed primary winding is still used to diminish the leakage, etc., yet it is not so essential as in the induction motor, since the primary has no longer to produce the magnetization. The secondary winding is usually of the concentrated type since it revolves with the flux wave and does not cut it. Under the same heading we must include induction machines in which the secondary is excited by low-frequency currents from what is called a phase advancer. In this case the secondary power is not strictly zero but it is absorbed by secondary resistance.

The function of the phase advancer, which is a small, low-frequency dynamo, is to produce a current in the secondary which is in quadrature with the load current and so capable of producing magnetization. This phase advancer may also be made to supply the secondary I^2R loss, whereupon the slip is reduced to zero and the machine becomes synchronous. This case only differs from that of the ordinary synchronous machine in that the position of the flux wave relative to the secondary, though invariable during running, may be adjusted to have any position instead of being fixed by the construction of the machine.

3. *Polyphase Commutator Machines.* The third type having a commutator on the secondary may be regarded firstly as a mere constructional modification of the induction machine, the advantage of the use of a commutator lying in the greater flexibility attained. In fact it is quite clear that if for the squirrel cage rotor mentioned above we substitute a commutator rotor with all the brushes short-circuited no alteration in the characteristics will be produced.

Suppose the commutator rotor to have the same number of turns as the primary. Instead of short-circuiting the brushes, suppose the stator to be fitted with a second or neutralizing winding having the same number of turns as the rotor or the primary and connected in series with it in such a manner that the two together form a non-inductive circuit. Thus the commutator rotor is connected into the star of the neutralizing winding on the stator.

Now suppose the polyphase line connected across rotor and neutralizing winding, and let us consider what happens. The rotor voltage is still zero since it is still running in synchronism with the flux, but the same e. m. f. is induced in the neutralizing winding as in the ordinary primary winding since the two may be exact duplicates of one another lying in the same slots.

This e. m. f. therefore balances the primary e. m. f. Since the ampere turns of the rotor and neutralizing winding are exactly equal and opposite they exert no inductive effect on the original primary winding and it is therefore relieved of all currents except magnetizing currents and its section may be proportionately diminished.

So far we have achieved nothing but a constructional modification of the induction machine but we now begin to see how this construction may be turned to advantage.

As soon as we depart from synchronism, an e. m. f. appears across the commutator brushes which, multiplied by the current, is a measure of the secondary power. Owing to the presence of the commutator, this secondary power always appears at line frequency and is absorbed direct from the line above synchronism and returned direct to it below. Hence such machines are capable of giving adjustable speed operation whether connected shunt or series, and this is their chief claim to existence.

4. *The Direct-Current Machines.* The fourth modification of the fundamental induction machine is that in which the commutator is interposed between the line and the primary winding and consequently the primary receives a frequency different from that of the line. The most prominent example of this class is the direct-current machine in which a wave of current density revolving relative to the primary of the machine is produced from the d-c. supply by the commutator. The magnetization which may be shunt or series is of the low-frequency type derived direct from the line and of course the secondary power zero. Since the primary frequency is due only to the rotation of the machine, the machine must always notwithstanding its adjustable speed be of the synchronous type. If a machine of type 3 be run very much above synchronism the secondary power will be much greater than the primary, and it will gradually approach the fourth class which is the limit towards which the third class approaches as the frequency tends to zero. All those exciters, phase advancers, etc. adapted to deal with currents of slip frequency must be placed in this fourth class, though the distinction between the third and fourth class will be more in the frequency of supply relative to that of rotation than otherwise. In the accompanying table have been written down the various permutations of the different alternatives contained in our four classes, excluding those which are obviously self-contradictory. It will be seen that there is not a very great number of permutations and of these some are impossible or at least unknown while some are merely special cases of others, occurring only at a particular speed (synchronism). Thus, finally, of all the possible permutations, only four distinct types of machine emerge—those briefly described above, all of which may be derived from one another by simple mechanical processes of inversion, etc. Thus starting from the d-c. machine we may (1) replace the commutator by a polyphase set of collector rings and we have a synchronous machine; (2) replace the field winding by a squirrel cage and we have the induction type; (3) invert, making the secondary the rotor, replace the squirrel cage by a commutator carrying a polyphase set of short-circuited brushes and reconnect the brushes in the manner described above, and we have the polyphase commutator type. These constructional modifications have one of two objects:

(a) Adaptation to different kinds of current as when we change a direct-current to a polyphase machine.

(b) To obtain characteristics adapted to some particular variety of industrial work as when we change the induction to the commutator type. It should be recognized however, that, in spite of all variations, there is but one dynamo-electric machine retaining its main features unchanged throughout. It is interesting to note that machines with series characteristics invariably have commutators.

CIRCULAR OR CONSTANT INTENSITY FIELD MACHINES

Name	Disposition of secondary power	Commutator	Magnetization	Shunt or series	Remarks
1.	Zero or absorbed by secondary resistance	absent	H.F.	Series	Impossible or unknown
2. Induction machine		"	"	Shunt	
3.		"	L.F.	Series	Impossible or unknown
4. Synchronous machine		"	"	Shunt	
5.	"	on primary	H.F.	Series	
6.	"	"	"	Shunt	
7. D.c. series mach.	"	"	L.F.	Series	
8. D.c. shunt mach.	"	"	"	Shunt	
9. Polyphase commutator series mach.	"	on secondary	H.F.	Series	The secondary power is only zero at synchronism so these machines are only special cases of the next four
10. do. shunt	"	"	"	Shunt	
11. do. series compensated	"	"	L.F.	Series	
12. do shunt	"	"	"	Shunt	
13. Comm. series mach.	Returned through Commutator	on secondary	H F.	Series	
14. Do. shunt		"	"	Shunt	
15. Do. series compensated	"	"	L.F.	Series	
16. Do. shunt			"	Shunt	
17. Induction mach.	Used in separate apparatus	absent	H.F.	Series	
18. Cascaded with	"	"	"	Shunt	
19, 13, 14, 15 or 16	"	"	"	Series	
20.	"	"	"	Shunt	
CONVERTERS					
Induction	Absorbed by secondary resistance	on primary	H.F.	Shunt	
Synchronous	Zero	"	L.F.	"	
Commutating frequency converter	Wattless	"	H.F.	"	
	"	"	L.F.	"	

NOTE: " H.F. " is an abbreviation for " high-frequency " and " L.F. " for low-frequency.

CONVERTERS

Various types of converters exist calling for a place in our classification. The function of a converter is essentially to produce a change in frequency and hence when it consists only of a single machine it is invariably of the commutator type. Such an apparatus (in the ideal case) is not called upon to develop torque and hence no secondary power exists. Certain types of frequency converter are fitted with field windings whose sole purpose is to produce a flux. In this case the secondary power is wattless or reactive, the only possible case of reactive secondary power in a circular field machine. Converters to operate on constant voltage must necessarily be shunt machines.

ELLIPTIC FIELD MACHINES

When we come to elliptic field machines an entirely new set of possibilities presents itself. The secondary power in such a machine may be reduced to zero though neither the secondary e.m.f. nor current are zero. Moreover in certain cases it may become entirely wattless a case which cannot occur in circular field machines. An elliptic field machine must necessarily have a commutator, since any machine having a short-circuited or separately-excited secondary must necessarily give rise to a circular field.* Owing to the presence of this commutator the secondary power when it exists appears at line frequency, and there is therefore no difficulty in returning it to the line or deriving it therefrom. In dealing with circular field machines we found it useful to draw a distinction between the cases in which the commutator was on the primary or on the secondary and we shall still find it useful to draw the same distinction. It enables us to divide our machines into two classes containing pairs of machines which may be shown to be exactly reciprocal to one another. For instance dealing with single-phase series type motors we may divide them into a number of pairs as follows:

Name	Commutator	Field	Secondary coil	Primary coil
Neutralized Series	Primary	Stator	Stator	Rotor
Compensated Repulsion	Secondary	Rotor	Rotor	Stator
Inverted Repulsion	Primary	Rotor	Stator	Rotor
Ordinary "	Secondary	Stator	Rotor	Stator
Induction Series	Secondary	Stator	Rotor	Stator
Comp. Inverted .... Repulsion Motor	Primary	Rotor	Stator	Rotor

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*The case of continuous dissipation of power, as in the single-phase induction motor operating below synchronism, is considered to be excluded by the assumption that we are dealing with "ideal" machines.

Diagrams of these machines are shown in Figs. 4, 5, 6, 7, 8 and 9. The last machine, which I have provisionally called the compensated inverted repulsion motor, is shown in Fig. 9. It has never been discussed as far as I am aware yet it is quite as practical a type as any of the others and may even have some advantages. Let us now consider in what manner the secondary power is disposed of in some of these pairs of machines. In the repulsion motors, ordinary and inverted, the secondary circuits are completely short circuited and hence the secondary power zero. In the neutralized series and compensated repulsion motors, as also in the last pair, the secondary power is used entirely for magnetizing and is therefore wattless. If the magnetization is of the low-frequency type, as in the compensated repulsion motor, the secondary power* vanishes completely at a particular speed (synchronism). The distinction which we have drawn between machines having the commutator on the primary and on

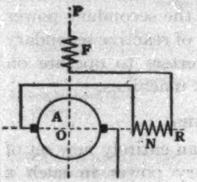

FIG. 4

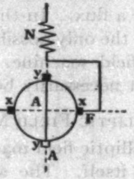

FIG. 5

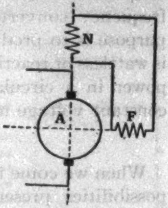

FIG. 6

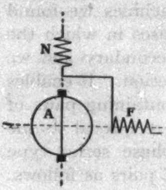

FIG. 7

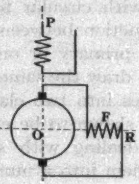

FIG. 8

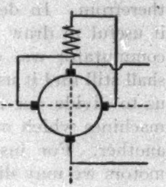

FIG. 9

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*It should perhaps be mentioned that by "secondary power" we mean the actual power measurable by a wattmeter and not any fictitious quantity such as some theories accustom us to consider.

the secondary merely symbolizes other important differences. Machines with commutator on the primary are "pulsating field machines" having a field distribution of the well known type characteristics of the neutralized series motor, viz., having a definite axis fixed in space. Such machines may conveniently be built with salient poles. Machines with commutator on the secondary are "revolving field machines" in which the field revolves elliptically at all speeds, becoming circular, as a rule, at synchronism. Such machines require an induction motor type of stator with uniform air gap all around. There are moreover important differences between the commutation of the two types. In the "revolving field type," since the flux revolves with the armature at synchronism, the commutating conditions are identical at this speed with those in direct-current machines. In the "pulsating field type" of course no such conditions exist, hence the above mentioned distinction symbolizes a large number of practical differences independent of any theory. Moreover the same distinction has been shown to be significant with reference to all standard types of machine also. In order to discuss the elliptic field machines more fully it is necessary to enter upon their theory to a certain extent. The writer has accustomed himself to think in terms of a certain theory which is described in a treatise entitled "Single-Phase Commutator Motors" published by him in 1913. Although this method of studying elliptic field motors is not at present very widely known it presents considerable advantages, and it will accordingly be made use of here. The purpose of the following discussion, however, is purely that of explaining the two reciprocal classes of single-phase series type motor which have been mentioned above, and as it adds nothing further to our results, may be omitted by the reader who is unfamiliar with the methods used, and who is willing to take for granted the reciprocity of the two classes.

POWER CALCULATIONS IN ELLIPTIC FIELD MACHINES

The secondary power is now the product of an elliptically distributed e.m.f. and an independent elliptically distributed current which may have quite different axes from that of the e.m.f. The multiplication of such ellipses has been discussed in the writer's "Single-Phase Commutator Motors," Appendix, pp. 108-109, where two products, the "sine" and the "cosine" product, are defined as follows: Suppose we wish to multiply any two vector ellipses, we must resolve each into a pair of conjugate diameters which will be in quadrature with one another. These are shown in Fig. 10 as ab and $a'b'$ and they must be so chosen that a is in phase with a' and b with b'. If α is the angle between a and a' and β that between b and b' we define the "cosine" products of the two ellipses as $a\,a' \cos \alpha + b\,b' \cos \beta$. If one ellipse represents a current distribution and the other an e.m.f. distribution, then " cosine " product represents the maximum power flowing due to the two, and $\frac{1}{2}(a\,a' \cos \alpha + b\,b' \cos \beta)$ is the mean power. In the case, in which both ellipses reduce to circles, we have $a = b, a' = b'\ \alpha = \beta$ so that the mean power will be $a\,a' \cos \alpha$ which is the usual expression. Since a is in quadrature with b' and b with a' we have not considered the products of these terms, as they will give rise to purely wattless or reactive terms. It is quite clear that the above expression may be reduced to zero in many ways without either of the factors being zero and hence the secondary power of our elliptic field machines may be zero or purely wattless without either the secondary current or e.m.f. being zero. Hence, such machines are not restricted to synchronous speed in the absence of some means of disposing of the secondary power as are machines of the circular field type. We shall now discuss some of the principal cases in which such a product may be zero without either of the factors vanishing.

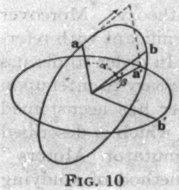

FIG. 10

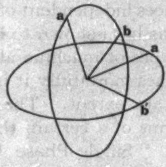

FIG. 11

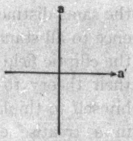

FIG. 12

1. Ellipses similar and of similar phase and at right angles to one another (see Fig. 11). In this case $\alpha = \beta = 90$ deg. and the product is wattless since neither $a\,b'$ nor $a'b$ are at right angles.

2. Each ellipse reduces to a straight line, both being at right angles (see Fig. 12). In this case the product is accurately zero, not wattless, and this is the only case in which it is accurately zero except with a circular field at synchronism

$$a\,a' \cos \alpha = -\,b\,b' \cos \beta$$

In this case the two ellipses rotate in opposite directions. We shall not come across any instance of this. Let us now consider what distributions of current and e.m.f. occur in some of the best-known types of single-phase motor having series characteristics. Consider first the case in which the commutator is on the primary. This case includes two well known types, the neutralized series motor and the inverted repulsion motor. Both of these involve a stator element which is or permissibly may be short-circuited.

1. Taking the inverted repulsion motor first: In the stator or secondary element the current flows entirely in the short circuited coil and will be represented by a straight line ellipse parallel to the axis of that coil. Since the coil is short-circuited the flux cannnot interlink it and must be therefore of the "pulsating" type represented by a straight line ellipse perpendicular to the axis of the coil. The same ellipse may also represent the e.m.f. to a suitable scale if we displace the phase by 90 deg. Hence, in this case, the two ellipses of e.m.f. and current reduce to two straight lines at right angles and the "cosine" product is therefore accurately zero (see Fig. 13). The ampere-turns necessary to excite the flux are of course supplied by the primary.

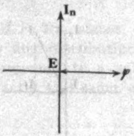

FIG. 13

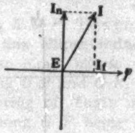

FIG. 14

2. *The Neutralized Series Motor* also contains a short-circuited element on its stator or secondary, viz., the neutralizing coil. For the same reasons as stated above, the current I_n in the neutralizing coil and the flux and e.m.f. will be represented by two straight line ellipses at right angles (see Fig. 14). In the present machine, however, the magnetizing ampere-turns necessary to excite the flux are on the secondary, being supplied by the field winding. The field currents will be represented by another straight line ellipse I_f parallel to φ and the resultant stator current by I. Thus since I and E are no longer at right angles their product will not be accurately zero, but since they

are still in quadrature it will be wattless. We shall now turn to the machines of the "rotating field" type which are reciprocal to the two just discussed, viz., the ordinary and compensated repulsion motors.

3. *The Repulsion Motor.* In the rotor or secondary element the current flows entirely in the short-circuited circuit and will be represented by a straight line ellipse parallel to the axis of that circuit. The e.m.f. across any short-circuited circuit is obviously zero, and the e.m.f. ellipse therefore reduces to a straight line perpendicular to the first, though of course it no longer follows that the flux is of the same form. Thus the rotor e.m.f. and current ellipses of the ordinary repulsion motor are identical with the stator e.m.f. and current ellipses of the inverted repulsion motor (see Fig. 15).

4. *The Compensated Repulsion Motor* also contains a short-circuited element on its rotor or secondary. For the same reasons as in the ordinary repulsion motor, the current in the short circuit I and the e.m.f. will be represented by two straight line ellipses at right angles (see Fig. 16). In this machine, however, the magnetizing ampere-turns necessary to excite the flux are on the secondary, being supplied by the circuit through the field brushes. The field currents will be represented by another straight line ellipse I_f parallel to E and the resultant stator current by I. Thus since I and E are no longer at right angles their product will no longer be accurately zero, but since they are still in quadrature it will be wattless (reducing to zero at synchronism, however, since in this machine low-frequency magnetization is made use of). In the above discussion only the secondary e.m.f. and current distributions are considered but it is easy to show that primary e.m.f. and current distributions are reciprocal also. In order to bring this out in its clearest form we may paraphrase the discussion in "Single-Phase Commutator Motors", pp. 51, 52, 53, in two parallel columns:

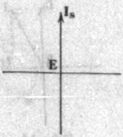

FIG. 15

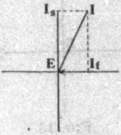

FIG. 16

The Repulsion Motor Rotor E.M.F. Since the rotor is short-circuited along the axis $O\,P$ there can be no e.m.f. along that axis and the rotor e.m.f. ellipse is therefore a straight line along $O\,R$ perpendicular to $O\,P$.

Flux Distribution. Such a rotor e.m.f. distribution can only be produced at speed K by a flux ellipse whose axes lie along $O\,P$, and $O\,R$, that along $O\,R$ being of length a say that along $O\,P$ being Ka, where K = speed synchronism. In this case the "Transformer" e.m.f. and e.m.f. of rotation along the short circuited axis $O\,P$ will cancel leaving a straight line distribution of rotor e.m.f.

Stator E.M.F. The stator e.m.f. due to this flux distribution will also be represented to a suitable scale by exactly the same ellipse as the flux.

Terminal E.M.F. This ellipse must touch a line perpendicular to $O\,Q$ and at a distance OE from the origin equal to the maximum terminal e.m.f.

The Inverted Repulsion Motor Stator E.M.F. Since the stator is short-circuited along the axis $O\,P$ there can be no e.m.f. along that axis and the stator e.m.f. ellipse is therefore a straight line along $O\,R$ perpendicular to $O\,P$.

Flux Distribution. Such a stator e.m.f. distribution can only be produced by an exactly similar flux distribution which may be represented to an appropriate scale by exactly the same straight line ellipse.

Rotor E.M.F. This purely single-phase flux ellipse induces in the rotor an e.m.f. ellipse whose axis lie along $O\,P$ and $O\,R$, that along $O\,R$ being of length a say, and that along $O\,P$ being Ka.

Terminal E.M.F. This ellipse must touch a line perpendicular to $O\,Q$ and at a distance $O\,E$ from the origin equal to the maximum terminal e.m.f.

SHUNT TYPE MACHINES

There is by no means so large a variety of shunt type as of series type motors having different modes of operation though substantially the same characteristics. Although the number of constructional modifications which may be suggested is, of course, endless, all practicable types of motor reduce, in the end, to what is essentially one machine. This is due to the following facts.

Consider the ordinary shunt motor operated on alternating current. If the armature current is approximately in phase with the line e.m.f., which it should be, of course, for operation on good power factor, it will be in quadrature with the flux, which lags 90 deg. behind the line e.m.f. In order therefore, to keep the flux and current in phase we need to supply the field with an e.m.f. leading 90 deg. on the armature or line e.m.f.

There is but one way to generate such an e.m.f., if we are to retain a purely single phase-motor, and that is by means of a pair of brushes arranged on the armature at right angles to the load brushes or those which carry the main current. The practical machine in which this principle is carried out in its simplest form is usually called the Atkinson commutator induction motor. It consists of a distributed single-phase winding on the stator, a pair of short-circuited brushes co-axial with the stator winding, and another pair at right angles thereto, also short-circuited.

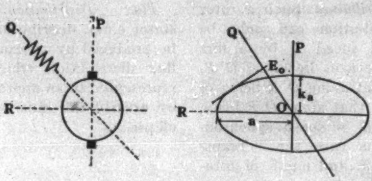

Fig. 17

The e.m.f. of rotation induced in this latter pair of brushes by the primary flux leads 90 deg. on the line e.m.f. and is therefore capable of producing the field we require. This commutator armature with its two pairs of short-circuited brushes may be replaced by a plain squirrel-cage armature giving us the ordinary single-phase induction motor. Such a machine is of the "rotating field" type and is therefore capable of low-frequency magnetization, otherwise known as compensation, by a well-known method. Such a machine is the single-phase

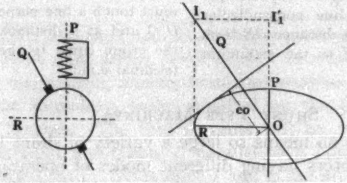

Fig. 18

representative of the polyphase or circular field machines discussed above, and in fact, a polyphase commutator machine of which one phase has been disconnected will, if of the shunt type, continue to operate on single phase just as an induction motor will. Our principles of classification do not necessitate any distinction being drawn between single-phase and polyphase machines so long as the fields of both remain circular. The principal utility of these single-phase commutator shunt machines is as adjustable speed machines, and two methods exist for varying the speed from synchronous:

1. By introducing power into the appropriate rotor circuit (see Fig. 19) by means of a transformer in exactly the same way as in the case of three-phase motors. Our principles as mentioned above do not necessitate a distinction being drawn between the single- and the three-phase case.

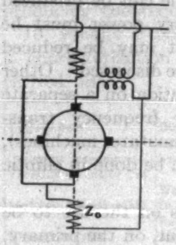

FIG. 19

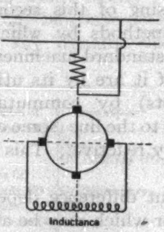

FIG. 20

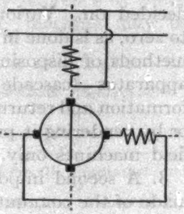

FIG. 21

2. A method peculiar to the single-phase motor, consisting in weakening the field perpendicular to the stator axis by means of reactance or an auxiliary coil placed in series with the field brushes. In this case the rotor power is no longer zero but wattless, being that consumed by the reactance or by the auxiliary coil. This method of weakening the field is shown in Figs. 20 and 21.

SUMMARY

We may now summarize the results of our discussion and make some final suggestions as to the best methods of classification.

1. The classification to which we have been led by the above discussion first of all subdivides our machines into:

(*A*) Circular field or constant intensity field machines, including all direct-current and balanced polyphase machines, all the standard types, in fact.

(*B*) Elliptic or variable intensity field machines, including single-phase and unbalanced polyphase apparatus.

(*C*) Multiple polarity apparatus such as the Hunt internal cascade machine and the split pole converter whose operation depends on the presence of harmonics in the main field. No detailed discussion of this class is attempted.

(*D*) We may regard homopolar machines as a fourth class.

2. It is shown from general mechanical considerations that electric power is developed in both the primary and secondary element of the general induction machine which is taken as typical, and that before an operable machine can be produced some method of disposing of this secondary power must be decided on. Various methods by which it may be reduced to zero, as is done in all standard machines are discussed. Other methods of disposing of it are by its utilization on a separate apparatus (cascade sets) by commutator frequency transformation and returning to the line (some commutator machines), or by rendering it purely reactive. This can be done in elliptic field machines only.

3. A second important difference depends on the use to be made of the commutator which may be absent, on the primary, or on the secondary. Except in d-c. machines the commutator is only useful for obtaining adjustable speed.

4. A third difference, not so important as the above two, depends on the method of magnetization. Two different methods of magnetization are distinguished, viz., "high-frequency" magnetization leading to the appearance of considerable reactive power on the line, as in the ordinary induction motor, and "low-frequency," as in the synchronous and compensated types.

5. Lastly, many types may be connected either series or shunt.

6. A table is constructed showing all possible combinations of these five sets of alternatives, and it is shown that they cover all known types of "constant intensity field" machines and that when the place of any apparatus in the table is assigned it can only be constucted in one way.

7. Coming to the elliptic field machines we find that the secondary power can be reduced to zero or a purely wattless form in many ways without either secondary current or e.m.f. being zero.

8. Our second principle of classification according to whether the commutator is on the primary or secondary leads us to distinguish elliptic field series type machines into two classes: "pulsating field" machines—the neutralized series motor and the inverted repulsion motor, and "elliptically rotating field" machines—the ordinary and compensated repulsion motor, etc. It is shown that a certain reciprocity or duality exists between these types whereby stator e.m.f. and current distribution on the one type is exactly the same as rotor e.m.f. and current on the other. The two types are distinguished by different constructional features, salient poles in the one type and uniform air gap in the other, and by differences in commutation.

9. Shunt type machines when purely single-phase are invariably of the rotating field type, as there is only one way of producing the requisite shunt field.

10. Finally a table may be constructed by reference to which a characterization of any dynamo-electric machine may be carried out.

Type of field	Disposition of Sec. Power (A)	Commutator	Magetization	Series or Shunt
Constant Intensity (C)	Zero (1)	None (N)		
Variable Intensity (V).		On Primary (P)		
	Wattless (2)			
Multiple Polarity (M).	In Cascade (3)	On Secondary (S)	High Fre. (H)	Series (Se)
Homopolar (H)	Returned to line by Trans(4)		Low Fre. (L)	Shunt (Sh)

From this table a machine may be characterized, as for instance: *C—A*1—*P—L—Se* would be the direct-current series machine, or *V—A*1—*P—H—Se* the inverted repulsion motor. Some possible combinations of lettering will be found self-contradictory. The principal test which we can apply to our system is to ascertain whether an apparatus can be denoted quite unambiguously by this lettering or whether several kinds of apparatus having legitimate claim to be regarded as different, and not as mere constructional modifications of one another, are denoted by the same lettering. The writer has tested it in this way to a certain extent, but an independent critic might be able to reveal difficulties not at present apparent. Of course, the present paper does not pretend to be more than a step in the direction of classification, and some modification of the present, or an entirely different scheme, might be found necessary.

DISCUSSION ON "CLASSIFICATION OF ALTERNATING-CURRENT MOTORS" (FYNN), AND "THE CLASSIFICATION OF ELECTROMAGNETIC MACHINERY" (CREEDY), DEER PARK, MD., JUNE 30, 1915.

A. S. McAllister: Mr. Creedy mentions several types of motors according to his classification, (*A*), (*B*), (*C*) and (*D*). Under (*A*) he includes balanced polyphase machines and under (*B*) he includes elliptical field machines, such as single-phase and unbalanced polyphase apparatus. He states that the elliptical field machines must necessarily have a commutator. Therefore, in the elliptical field machines he does not include the single-phase induction motor without a commutator.

I wish to call attention to the fact that an elliptical field machine does not necessarily have a commutator. An elliptical field, if I have a proper idea of what the author means by that term, is a field which is elliptical in time and space.

The author calls attention to what he says is a new type of machine, which has never been discussed, so far as he is aware. He refers to what he has provisionally called the compensated inverted repulsion motor. He is evidently familiar only with English practise, because the machine mentioned by him has been fully set forth in the records of the Patent Office of the United States.

Mr. Fynn has called attention to certain fundamental principles in the operation of commutator machines; the division of the machine into its two parts, the torque-producing field and the current which produces the torque against the field. I believe that practically all of the differences in opinion of people who are more or less familiar with the various types of machines have been due to the fact that they have ignored this one fundamental principle. In order to determine how a machine operates, one must divide it up according to the principle laid down by Mr. Fynn. I believe that there is no other logical and proper method. There may be other methods of defining what is meant, but in the end, if one wishes to determine the characteristics of the machine, he must base his equation on assumptions which must be identical with what Mr. Fynn has presented in order to get correct results.

H. M. Hobart: The work of the Standards Committee will be much assisted by these two papers. I should suppose that the sub-committee of the Standards Committee which deals with nomenclature would give careful study to both papers, and profit by the suggestions. I doubt, however, whether either the one scheme or the other, if adopted, would work out very well in practise. It seems to me that Mr. Fynn's object can be accomplished much more effectively by regarding his names more as *abbreviated definitions*. As such they are exceedingly useful. For practical use we need something much more brief than some of these many-worded titles. It is enormously difficult to force the use of terms. I do not recall exactly when it was, but at one time the American Institute of Electrical Engineers decreed that a certain machine should no longer be called a rotary converter, but should be called a synchronous converter. Unfortunately the former designation is still the more usual. I take that as a single but typical instance.

The papers we have considered this morning are very important and useful contributions to a very difficult subject. When we hear some one allude to a repulsion motor, there is vividly conjured up in our imaginations the type of motor to which the man refers. The correctness of the designation is immaterial. If some one speaks to me of a Mallet, I see vividly at once something which, if he gave me a full description of it, he would have to talk about for a long time. It means a distinct type of locomotive. He might have to qualify it by giving certain details of it, this, that or the other kind or size of Mallet, but the general type of machine is brought, like a flash, into my mind when he speaks of a " Mallet." This would not be the case if you speak of its articulated construction, number of axles, arrangement of driving wheels, etc. He alludes to it as a Mallet, and I know what he means. He is alluding to a special thing, which my mind immediately grasps.

While we cannot *always* approach this degree of brevity, there are plenty of similar instances. For example, we speak of the Hall effect, the Peltier effect, the Wheatstone bridge, the Blake transmitter, the Siemens dynamometer, the Kelvin balance, the Edison battery and the Daniell cell. The name of the man associated with the conception or development of a certain class of apparatus appeals to us very strongly, and this association of the man's name with the apparatus becomes very useful in identifying these things. It really does not make any difference whether the credit is correctly bestowed or not. We do not really care whether a man named Mallet first conceived the particular type of locomotive bearing his name. We know it as an object called a " Mallet," and that means much to us, quite dissociated from the fact that Mallet was the man who invented the engine.

The fact is that in this particular subject under discussion the names which have, rightly or wrongly, come to be associated with these motors have already helped a great deal. We cannot with certainty determine who is responsible for this, that, or the other type of a-c. single-phase commutator motor, taking that class of motors alone amongst these machines which have been mentioned. Let us confine our attention to single-phase commutator motors for the present. So many workers have been contemporaneously engaged in the development of these types of machines that it would be absolutely impossible to trace correctly the steps by which these machines have been evolved. It is sufficient that certain names are associated with certain types amongst these machines, or else with certain features of their operation. For instance, the feature of power factor correction in such a motor may be associated with a certain man's name, say Fynn. Many other names are closely associated with alternating-current commutator motors. Thus there is Atkinson, who wrote a brilliant paper on commutator motors many years ago, describing many of the types which are now becoming familiar to us in practise. Then there are Elihu Thomson, Arnold, Weightman and Heyland. At a later period we have Latour, Winter, Eichberg, Déri, Fynn, Punga, Creedy, Alexanderson, Milch, and, more recently, Scherbius and Krämer.

Now, as I say, it would not be worth while to try to figure out to which man the invention really is due—it never could be, with certainty, found out. The suggestion is just to follow the general impression and use the name which would be most naturally associated with a certain type, and it seems to me much help would be found there. The machines might be *defined* by the Standards Committee in much the way that Fynn and Creedy suggest defining them. Mr. Fynn's designations provide brief, compact descriptions of each type of motor. We must remember that other features already taken into account in the Standardization Rules also come into consideration. These relate to degrees of enclosure, regulation, etc. We should simply give a brief name to one type of alternating-current commutator motor, and then state whether it is of the enclosed or ventilated type, the particular kind of ventilation, and the output, speed, periodicity and voltage and also whether the rating is short time or continuous. There are many features requiring mention, so if we can use a man's name, (or any familar word, such as "repulsion"), as the means of describing the fundamental type, it will afford us great mental relief in many instances. I want to offer this suggestion for the consideration of the Nomenclature sub-committee of the Standards Committee.

Charles R. Underhill: This matter of definitions of motors is, perhaps, a little out of my line, but I am very much interested in the matter of standardization. Mr. Fynn's attitude in calling a neutralized single-phase series motor a neutralized single-phase series motor appeals to me very strongly. It tells what it is, and you do not have to look up the matter in the dictionary to find out what it is. On the other hand, I note that Mr. Creedy has shown a tabulation where he has used some symbols, some of them look like chemical symbols, but anyhow, it gives a condensed form of classification. You have all heard of the Taylor system, no doubt. In the company with which I am connected we never make the same article for two different customers. Everything is made on special contract, and large quantities are made, yet we have absolutely no difficulty in the classification of all of these things, not only the apparatus and type but the material as well. The Taylor system is a scientific thing and scientific management is becoming a recognized institution.

To begin with, let us take the former classification; let us take a neutralized single-phase series motor. In the first place, we can say that it is a motor. Any manufacturer of electrical apparatus in general who makes motors would know when seeing the symbol *M* that it stands for motor, and in the next position after it is placed the letter *S* which shows it is a series motor, and in the next position after that might be placed another *S* meaning that it is a single-phase motor. Then that could be followed by the letter *N*, which would show that it is of the neutralized type.

The symbol would then be *MSSN*.

In the Taylor system under this general classification come the sub-classifications, which naturally follow for the details.

Let us consider the practise of the manufacturing company referred to above. The symbol *KE*600*C*9187*VB* is an example of the designation of the finished product. *K* = coil; *E* = enamelite wire; 600 is the resistance in ohms, *C* indicates that the coil is of the controller type, 9187 is the code number, *V* means that the coil is treated with insulating varnish, and *B* indicates that the coil is mounted on a brass tube. Sometimes the dimensions are inserted between the letters in the symbol. The parts which enter into the construction have similar symbols, and the symbol for the parts, in the example cited, would begin with *KV*, meaning "for coils for various purposes", other following letters and numerals representing the material and dimensions.

The Taylor system is being used more and more by large manufacturing concerns; it is standard; is already in existence, and it seems to me that some form of classification in connection with those suggested in the papers would work with this system of scientific management right from the start.

H. M. Hobart: There was a technical matter in Mr. Fynn's paper which might be worth mentioning. I can combine and resolve *causes*, but I find it dangerous to try to combine and resolve effects. Mr. Fynn considers component fields. I get along fairly well as long as I consider component m.m.fs., but believe it is dangerous to deal similarly with the fields resulting from these m.m.fs. Such a plan is, in my opinion, beset with pitfalls. Mr. Fynn, in connection with his condemnation of the term "repulsion," laid special stress on the importance of not leading students astray by referring to a certain type of motor by a misleading name. Does he not run the risk of leading them astray in this other direction? I have struggled with Mr. Fynn's various papers during the last ten years and have found it necessary to look out for these pitfalls where he alluded to the component fields. I should like to know whether others have had similar experience, and whether it is agreed that I am right in my opinion that it is practicable and useful to combine and resolve *causes*, but that there is something wrong in trying to do that with *effects*.

Comfort A. Adams: This is a subject which I have had frequent occasion to discuss as a teacher, as much confusion is sure to develop in the mind of the average student unless he is thoroughly prepared to distinguish between the imaginary component fluxes and the real resultant flux. Nevertheless, it is in many cases absolutely necessary to compute these several component fluxes, often more than two, as if they existed separately, because of their intimate relation to the operating characteristics of the machines in question. Take, for example, the leakage fluxes of an induction motor; we speak of these as several independent fluxes, whereas we know as a matter of fact that they are mostly distortional in their nature and parts of the real total flux; that is, we artificially subdivide the actual flux into several components and compute them as if they were independent. There is a real danger here, and Mr. Hobart is quite right in emphasizing it; but it can be avoided by a sufficient emphasis upon the fact that the consideration of the component fluxes as separate fluxes is artificial and merely an aid to visualization and computation.

V. A. Fynn: I think I can answer Dr. McAllister's question as to Mr. Creedy's paper. I may be wrong, but it appears to me that Mr. Creedy includes the single-phase induction motor under (*A*), for he says: "Our principles of classification do not necessitate any distinction being made between single-phase and polyphase machines so long as the fields of both remain circular." I think Mr. Creedy believes that the field of a single-phase induction machine remains circular, and that this motor is therefore to be classed with polyphase motors.

It strikes me that Mr. Creedy's classification does not go quite far enough, and is based on incorrect conceptions. I think it is important, when talking to some one about a particular machine, to indicate clearly whether reference is made to a single-phase or a polyphase machine. The differences are quite essential. To illustrate this, take Mr. Creedy's contention that the machine shown in Fig. 19 does not necessitate a distinction being drawn between the single- and the three-phase case, for regulation is obtained in exactly the same manner in both. I do not agree with him at all. Mr. Creedy proposes to regulate the single-phase machine, Fig. 19, by injecting an e.m.f. into what I call the armature circuit. The result is to either lower or increase the speed without changing the magnitude of the field in the vertical axis. But if the speed is increased or decreased, the magnitude of the field in the horizontal axis is changed. If you apply the same method of regulation to, say, a two-phase motor, then you change its speed but do not change either its vertical or its horizontal field. The reason is simple—in the polyphase motor the rotor acts as an armature in both axes, while in the single-phase machine it acts as an armature in the vertical axis and as a field in the horizontal axis. In the single-phase motor, a change in speed alters the magnitude of the horizontal or motor field, whereas all motor fields in a polyphase motor depend on the e.m.f. applied to the stator windings and are independent of the speed.

Mr. Creedy has stated that he preferred to leave things as they are and not change well-established names. He, however, refers to the d-c. series machine as *C-A*1-*P-L-Se*, which is probably a mistake for *V-A*1-*P-L-Se*. If we translate this we get: Variable intensity field, secondary power zero, commutator on primary, low frequency magnetization, series motor, as a substitute for the generally accepted name, d-c. series motor. Note that after we have said all Mr. Creedy suggests, nobody will know whether we have reference to a d-c. or to an a-c. machine, whether it is neutralized or not, and if neutralized, whether it is so conductively or inductively.

I think Mr. Hobart's suggestion, to give coined names to these various motors, is well worth considering. I do not care whether the names agreed upon are the names of the alleged inventors or coined words just like the word "repulsion," but I clearly see the difficulties of such a course. Some of us lay claim to the invention of several motors, and a dictionary defining the meaning of coined words will be indispensable. For my own part I will be very glad to accept the word repulsion, but before agreeing to it, a definition of the term must be insisted upon. Apply the term repulsion motor to any machine you care to select for the purpose, but confine its use to that particular motor, for the term can have but one meaning.

W. C. Korthals Altes (communicated after adjournment): In Fig. 13, Mr. Fynn shows the well-known repulsion motor and suggests as a substitute for this historical name, "self-excited single-phase series induction motor with rotor excitation".

I think it is unnecessary to raise serious objections to any attempt to introduce this name. The well-known American habit of shortening even the simplest Christian name is the best safeguard against such a mouthful being imposed upon us.

In Fig. 14, he shows the same repulsion motor with a somewhat different arrangement of the stator winding and suggests the name "single-phase series induction motor".

In his descriptive outline he mentions that with a motor according to Fig. 13, "the power factor rises to near unity at about synchronism", while with a motor according to Fig. 14, " the power factor is low at all speeds ".

I have never known of this marked difference between these two motors and should like to ask Mr. Fynn whether he has found that his theory is confirmed by test.

In Fig. 1, I have shown a bipolar repulsion motor having 12 stator slots, containing a concentric stator winding, the brushes being shifted over 30 deg. The stator winding can be resolved into a component consisting of the conductors lying between the angles *aOb* and *cOd*, which excites the field flux, and a component between the angles *bOc* and *dOa*, which constitutes the compensating winding, from which the power is induced by transformation into the rotor. In opposition to Mr. Fynn, I contend that the current between the brushes will assume such a value that the secondary ampere-turns of all the rotor conductors equal the total number of stator ampere-turns lying between the angles *bOc* and *dOa*. This applies to standstill, when the ampere-turns required for exciting the transformer flux can be neglected. When the motor is running the transformer flux will increase with the speed and the secondary current will assume such a value and time phase that the vector sum of the secondary ampere-turns and the ampere-turns lying between the angles *bOc* and *dOa* excite the transformer flux. This corresponds to what happens in any stationary transformer.

My Fig. 1 corresponds to Fig. 13 of Mr. Fynn's paper. In Fig. 2, I have shown the motor which corresponds to his Fig. 14. It is clear that as far as the ampere conductors in the stator slots are concerned and their position in regard to the brushes, my Figs. 1 and 2 are identical. The only difference is that the conductors exciting the field, lying in both cases between the angles *aOc* and *cOd*, are interconnected by longer end-connectors in Fig. 2 than in Fig. 1. This means a slight increase in leakage reactance. Bearing in mind that commercial repulsion motors have about 10 per cent leakage reactance in the stator, it will be appreciated that this increase in reactance is only very slight, and cannot so materially affect the power factor as would follow from the above quoted statements by Mr. Fynn. In any case it seems perfectly arbitrary and contrary to fact to speak in one case of rotor and in the other case of stator excitation.

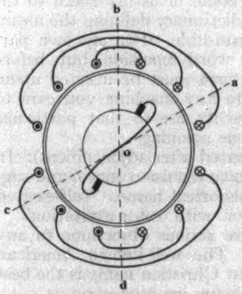

FIG. 1

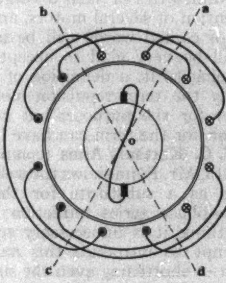

FIG. 2

In Fig. 3, I have shown the same twelve slots as in Fig. 1, the conductors in these slots being connected by a Gramme ring winding. It is clear that Figs. 1, 2 and 3 are identical, with the exception that in case of Fig. 3 the reactance of the end-connections is considerably higher.

That Mr. Fynn has an unusual conception of what is generally understood under rotor excitation is further illustrated by his outline of the theory for the motor shown in his Fig. 18. He claims that this motor has the same characteristics as the one covered by Fig. 13, " with this difference, that the whole rotor winding is made use of ".

This motor is, however, fundamentally different from the one shown in his Fig. 13, as it has what is generally understood by rotor excitation, which offers the possibility of operating the motor with approximately unity power factor at synchronism and full load.

A physical conception of what is generally understood by rotor excitation can readily be obtained by the following simple experiment.

A two-pole d-c. armature is driven by means of an auxiliary motor at approximately synchronous speed inside the stator of an induction motor. On the commutator slide four brushes, spaced 90 deg. apart and connected as per Fig. 4. If we apply a small a-c. voltage *v* as shown in Fig. 4, then a current will flow between the brushes 1 and 2 which excites an alternating flux along an axis coinciding with the brushes 1 and 2. Due to the alternation of the flux a voltage will be induced between the brushes 1 and 2 proportional to the flux and frequency, lagging 90 deg. behind the current. As the armature conductors rotate through this flux a voltage of rotation will appear at the brushes 3-4, proportional to the frequency of rotation and the flux. The frequency of rotation and of alternation of the applied voltage being equal at synchronous speed, the voltage appearing at the brushes 3-4 will at synchronous speed be equal to the voltage applied to 1-2. Its time phase will be the same as the current flowing between the brushes 1-2. If we now short-circuit brushes 3-4, a magnetizing current lagging 90 degrees

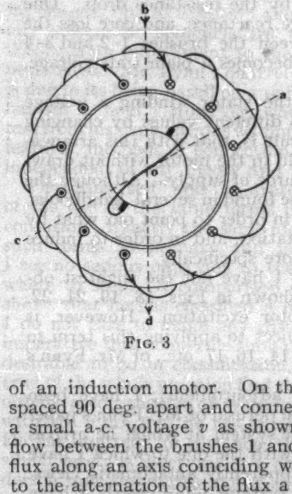

FIG. 3

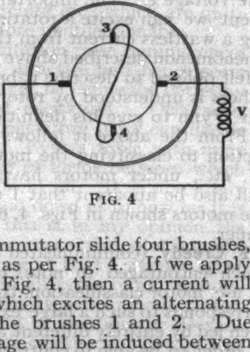

FIG. 4

in time phase behind the voltage will flow, exciting a flux, which by alternation induces a voltage, balancing the voltage generated by rotation. If the magnetic reluctance is equal in all directions this magnetizing current will be equal to the current flowing between the brushes 1–2. Again it is clear that due to the rotation through this last flux a voltage will appear between the brushes 2-1 having the same time phase as the magnetizing current flowing between the brushes 3–4, or measured from brush 1 to 2, instead of 2 to 1, will be 180 deg. ahead of the magnetizing current between 3 and 4 or 90 deg. ahead of the current between 1 and 2. We found that the current from 1 to 2 induced by alternation of the flux yielded thereby a voltage lagging 90 deg. in time phase, which in accordance with the above must be balanced at synchronous speed by the rotation voltage. Thus the voltage v can be in time phase with the current flowing from 1 to 2 and is merely determined by the resistance drop. Due to the commutation losses, leakage reactance, and core loss the speed at which the current between the brushes 1–2 and 3-4 becomes equal and the voltage v becomes a plain watt-voltage, lies somewhat above synchronism.

It will also be found that at the stator winding a voltage appears which can be adjusted to different values by changing the voltage v. The important result is, that with this arrangement we can excite a rotating field in the motor without drawing a wattless current from the source of supply. Although the phenomenon described above can be found in several handbooks, I felt obliged to describe it briefly in order to point out what by others is understood by rotor excitation, and in order to induce Mr. Fynn to give his definition more specifically.

From the above it follows that I have not the slightest objection to classifying the motors shown in Figs. 18, 19, 21, 22, 23, etc., under motors having rotor excitation. However, it will also be apparent that I do object to applying this term to the motors shown in Figs. 4, 6, 13, 14, 16, 17, etc., of Mr. Fynn's paper.

F. Creedy (communicated after adjournment): I have been much encouraged to note, on the perusal of Mr. Fynn's paper on a-c. motor classification, that the system at which he arrives corresponds to such a large extent with the one to which I have been led by entirely different and apparently antagonistic views. In order to be able to contrast the systems more clearly I have ventured to tabulate them in the two tables attached. Let us first discuss the points in which the two systems agree.

1. Series or shunt machines. Any system must preserve the classification into series and shunt types.

2. Single or polyphase. Mr. Fynn uses these words in a somewhat peculiar sense. For instance, Figs. 27 and 29, shunt machines in which the field is excited by a second phase, are classed by him as single-phase. In the sense employed by him, I maintain that his classification into single- and polyphase

machines is practically identical with mine into elliptic and circular field machines, since only *balanced* machines are referred to by him as polyphase.

3. Conduction and induction. This class corresponds very closely with my subdivision into "commutator on primary" and "commutator on secondary". The difference between them only arises in such a case as Fig. 46, where although it is a conduction motor the commutator element is nevertheless the secondary, *i.e.*, is *not* that in which the power supplied by the line is consumed.

We now come to the differences between the two systems. Mr. Fynn states at the outset that in order to arrive at a rational classification all suggestions must be based on one and the same theory and that his system is based on the component field theory. If this were really the case, I should be obliged, from my standpoint, to condemn the system radically, as I hold that any system or nomenclature which presupposes a particular theory is an impediment to the progress of science and should be avoided. Mr. Fynn's quarrel with the term "repulsion motor" is due to its being based on a particular theory which he does not happen to hold. However, when we separate Mr. Fynn's system from his explanations we find it to be based on constructional features, methods of connection of circuits, etc., which are quite independent of any theory and therefore unobjectionable.

The terms "self" and "separate" excitation raise reminiscences of the use of the same terms in d-c. practise and hence seem confusing. Exactly the same ideas might be expressed better by such terms as primary and induced excitation. Otherwise, I see no serious objection to the nomenclature if we can decide where to stop. A comparison of Mr. Fynn's table with mine shows that he has classified a number of forms between which I do not care to make any distinction at all. It is absolutely imperative that some rule should be laid down as to how far it is desirable to go in classification, and this is, in my opinion, the crux of the whole question and the most important point brought out by a comparison of systems. I regret that I cannot agree with Mr. Fynn that he has enumerated all types of a-c. motors. He has omitted, for instance, the ordinary synchronous motor, which surely is deserving of a place, not to mention the Alexanderson repulsion-series motor and hosts of others. Two patent specifications on single-phase shunt machines, one of them in Mr. Fynn's own name, contain, between them, descriptions of over one hundred different forms, many of them differing quite as widely as some of the types Mr. Fynn lists.

It is essential that some rule be found to decide which forms deserve a place and which forms do not. The object of the system I have developed, based on energy torque and power considerations, is (a) to avoid the necessity of adopting any particular theory of operation for any type, and (b) to supply a

CREEDY'S SYSTEM

Fig. No.	Field form	Secondary power	Commutator	Magnetisation	Series or shunt	
2	Elliptic	Reactive	Primary	H.F.	Series	
3	"	"	"	"	"	
4	"	"	"	"	"	
5	"	"	"	"	"	
6	"	Zero	"	"	"	
7	"	"	"	"	"	
8	"	"	"	"	"	
9	"	Reactive	"	L.F.	"	
10	"	"	"	H.F.	"	**Must be treated as motor and transformer combined.**
12	"	"	"	"	"	
13	"	Zero	Secondary	H.F.	"	
14	"	"	"	"	"	
16	"	"	"	"	"	
17	"	"	"	"	"	
18	"	"	"	"	"	
19	"	"	"	"	"	
20	"	Reactive	"	"	"	
21	"	Reactive (Zero at synchronism)	"	L.F.	"	
22	"	Reactive (Zero at synchronism)	"	"	"	
23	"	Derived from line by transformer	"	"	"	
24	Circular	Derived from line by transformer	"	H.F.	"	
25	"	Derived from line by transformer	"	"	"	
26	Elliptic	Reactive	Primary	H.F.	Shunt	
27	"	"	"	"	"	
28	"	Zero at normal speed.	"	L.F.	"	
29	"	Reactive	"	H.F.	"	
30	Circular	"	"	"	"	
31	"	"	"	L.F.	"	
32	Elliptic	"	Primary	H.F.	"	
33	"	Zero	Secondary	H.F.	"	
34	Circular	"	"	"	"	
35	"	"	"	L.F.	"	
36	Elliptic	Reactive	"	H.F.	"	
37	Circular	Zero	"	L.F.	"	
38	Elliptic	Reactive	"	H or L.F.	"	
39	Circular	Zero	None	H.F.	"	
40	"	"	Secondary	L.F.	"	
41	"	"	"	H.F.	"	
42	"	"	"	L.F.	"	
43	"	Derived from line.	"	H.F.	"	
44	"	Zero	None	"	"	
45	"	"	Secondary	L.F.	"	
46	"	"	"	H.F.	"	
47	"	"	"	L.F.	"	

FYNN'S SYSTEM

Fig. No.	Neutralization	Excitation		Conduction or induction	Series or shunt	Single or polyphase	Remarks
		Stator or rotor	Self or separate				
2	None	Stator	Separate	Conduction	Series	Single	
3	Conductive	"	"	"	"	"	
4	"	Rotor	"	"	"	"	
5	Inductive	Stator	"	"	"	"	
6	"	Rotor	"	"	"	"	
7	"	"	"	"	"	"	Two conductively related rotor circuits.
8	"	"	"	"	"	"	Two inductively related rotor circuits.
9	Conductive	Rotor		"	"	"	Two inductively related rotor circuits (Compensated).
10	None	Stator	Mixed	"	"	"	
11	Inductive	Rotor	Self	"	"	"	
13	None	"	"	Induction	"	"	
14	"	Stator	"	"	"	"	
16	"	Rotor	Self	"	"	"	Independent brushes.
17	"	"	"	"	"	"	Two independent rotor circuits.
18	"	"	"	"	"	"	Two inductively related rotor circuits.
19	"	"	"	"	"	"	Twoconductively related rotor circuits.
20	"	Stator	Self	"	"	"	
21	"	Rotor	Separate	"	"	"	
22	"	"	"	"	"	"	Different brush connection.
23	"	Rotor	"	Induction-Conduction	"	"	
24	Conductive	Stator	"	Conduction	"	Two-phase	
25	"	Rotor	"	"	"	"	
26	None	Stator	"	"	Shunt	Single	
27	Conductive	"	Separate	"	"	"	
28	"	Rotor	"	"	"	"	
29	Inductive	Stator	"	"	"	"	
30	Conductive	Rotor	Self	"	"	"	
31	"	"	"	"	"	"	Compensated.
32	"	Rotor and Stator		"	"	"	
33	None	Stator	Separate	Induction	"	"	
34	"	Rotor	Self	"	"	"	
35	"	"	"	"	"	"	Compensated.
36	"	Rotor and Stator	"	"	"	"	
37	"	Rotor	"	Ind.-Cond	"	"	
38	"	Rotor	Mixed	Induction	"	"	
39	"	"	Self	"	"	"	Single-phase induction motor.
40	"	"	"	"	"	"	Compensated motor
41	"	Stator	Separate	"	"	Two-phase	
42	"	"	"	"	"	"	Compensated.
43	"	"	"	Ind.-Cond.	"	"	
44	"	"	"	Induction	"	"	
45	"	"	"	"	"	"	Compensated.
46	Conductive	"	"	Conduction	"	"	
47	"	"	"	"	"	"	Compensated.

precise rule as to where classification should stop. This rule is as follows:

If two different constructional forms have the same physical properties, they should be classed together.

For instance, I consider it undesirable to attempt to separate Figs. 3, 4 and 5 from one another, though there are some differences, undoubtedly. Again, Figs. 13 and 14 seem to me identical and there are a number of other pairs which I think should not be distinguished or given an apparent predominance over the thousands of modifications possible but not alluded to. Still, if the general opinion of students of the subject is that constructional forms, even if physically identical, require distinction, then probably Mr. Fynn's system superadded to a system based on physical principles, is as free from objection as any not considerably more complicated.

To my mind, however, a far better plan is to frame standard rules for deriving different constructional forms from a given form. Two such rules, which may be quoted by way of example, are as follows:

1. By means of the Steinmetz transformer reduction we may replace any inductive type by a corresponding conductive type having, not approximately but exactly, the same flux distribution and the same characteristics.

2. Any two windings on the same member which are connected in series may be compounded into a single winding, and conversely, any single winding may be resolved into two windings in series.

These two rules alone are sufficient to show that many of the types listed by Mr. Fynn are only constructional modifications of one another.

While studying the present subject, a little book by Dyhr, "Der Einphasen-Motoren," which contains an extraordinarily complete account of every type proposed or patented up to the present, should be consulted.

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THE EFFECTIVE ILLUMINATION OF STREETS

BY PRESTON S. MLLAR

ABSTRACT OF PAPER

This paper mentions the dependence of effectiveness in street lighting upon municipal appropriations and efficient lamps, but discusses more particularly those aspects of effectiveness which are dependent upon skilful utilization of the light to produce the most effective illumination. There are included a classification of streets, a statement of the objects of street lighting and the elements of vision under street lighting conditions. The paper emphasizes three considerations which are sometimes neglected in street lighting discussions; namely, the silhouette effect, specular reflection from street pavements, and glare. The remainder of the paper is given over to a presentation of the variables upon which the effectiveness of street illumination depends, and upon the influence which each feature of the installation exercises through these several variables. As a part of this discussion illuminating efficiency values for the several modern street illuminants are given. The appendix includes statistics and photographs of some very recent installations which illustrate the latest trend in street lighting.

IMPROVEMENT in street lighting involves (1) larger municipal appropriations; (2) more efficient lamps and accessories; (3) greater skill in application.

Larger Municipal Appropriations. The public is gradually becoming acquainted with the advantages of more liberal use of light. Use of the streets at night is becoming more general throughout a greater number of hours. Requirements for good street lighting are becoming greater as traffic becomes denser and as traffic speed increases. Also the advertising value of extensively employed light is commanding appreciation in mercantile lines. These things combined are leading to larger municipal appropriations. Larger appropriations mean betterment in street illumination because the mere addition of lamps with no increase in lighting efficiency and no greater skill in application usually improves conditions. The greatest single obstacle to satisfactory street illumination is lack of funds.

More Efficient Lamps and Accessories. The last two years have witnessed increases of 25 to 50 per cent in efficiencies of street illuminants, the Mazda C incandescent lamp and the magnetite arc lamp having progressed contemporaneously. At the present time in the magnetite lamp of medium and high power, in the Mazda C lamp of low, medium and high power, and in the flame arc lamp of high power there are available illuminants having efficiencies four or five times greater than those of various types of enclosed carbon arc lamps which were the principal street illuminants in this country a few years ago. Some advance has been made also in the design of lamp equipments, notable among which are the prismatic refractor and a variety of light-density translucent glassware which combines fairly good diffusion with high transmission. These improvements in the materials of street illumination combined with the increased sums which municipalities are appropriating make possible a very general improvement in street lighting.

Skill in Application. Recently installed systems are almost invariably superior to the systems which they replace. Usually the improvement is due in part to greater skill on the part of the engineers in charge. City engineers, central station engineers and manufacturers are better acquainted with the problems and have acquired more skill in meeting them. The result is street illumination of greater effectiveness. Notwithstanding this advance there are but few principles of street illumination which are regarded as thoroughly established. Although the subject has received perhaps more than a fair share of discussion and study, it is still enveloped in much uncertainty. In the literature and in practise there is much which indicates differences of opinion in regard to principles of fundamental importance. It must be admitted that progress in the conception of correct principles is slow. Yet there is progress, and it may be that by the time most street lighting is made good, those of us who talk and write of the principles may reach an agreement as to what constitutes good street lighting.

It is the purpose of this paper to discuss the variables of street illumination and the principles underlying the best use of modern illuminants and accessories under modern conditions in this country. We shall consider therefore matters pertaining more especially to the third factor entering into improvement in street illumination as enumerated in the first paragraph.*

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*This paper may be regarded as a continuation of the discussion presented by the author before the 1910 convention of the Illuminating Engineering Society under the title "Some Neglected Considerations Pertaining to Street Illumination."

CLASSIFICATION OF STREETS

For the purposes of this discussion the following classification of streets is adopted:

CLASS	DESCRIPTION
1*a*	Metropolitan thoroughfares of greatest distinction.
1*b*	Important city streets largely traveled at night.
2*a*	Business streets not largely traversed at night.
2*b*	City residential streets.
3*a*	Suburban residential streets.
3*b*	Suburban thoroughfares.

It will be apparent that requirements for street illumination are diverse as among these different classes of streets. For example, the 1*a* class of streets is distinguished by a requirement for dignified, pleasing fixtures and for lamps and illumination which should be of fairly high intensity, lighting building fronts as well as street. Streets of the 1*b* class are likely to be characterized by much show-window and sign lighting which augments the street illumination during the hours of greatest traffic. Here intensities are likely to be highest, and the ordinary fundamental requirements of street lighting are supplemented by the desirability for recognizing acquaintances in the passing throng and for detailed vision, approaching that common to interiors at night.

In streets of the 2*a* class a moderate intensity of illumination which lights building fronts as well as street is customary. Policing purposes and good seeing conditions for the occasional pedestrian are the principal desiderata. In streets of the 2*b* class it is usually desirable to keep the light upon the street surface, avoiding brilliant illumination of the upper stories of residence fronts and providing fairly good lighting for the low density vehicular and pedestrian traffic.

In streets of the 3*a* class it is likewise desirable to keep the light upon the street, illuminating the sidewalks well to serve the purposes of pedestrians. In streets of the 3*b* class, which are the important automobile highways connecting populous centers, the principal requirement is that of the automobile driver. Here the most difficult problems of street illumination are encountered.

The discussion in this paper is applicable in varying degree to streets of these six classes.

OBJECTS OF STREET ILLUMINATION

From several points of view the objects of street illumination may be stated in somewhat different ways. The point of view of the motorist differs from that of the pedestrian which in turn differs from that of the police commissioner and from that of the merchant. When, however, one assembles the considerations growing out of all these several viewpoints, those of first importance appear to fall within the comprehensive classification presented by the National Electric Light Association Street Lighting Committee in 1914, which is as follows:

Fundamental Purposes to be Served by Street Illumination.

1. Discernment of large objects in the street and on the sidewalks.
2. Discernment of surface irregularities in the street and on the sidewalks.
3. Good general appearance of the lighted street.

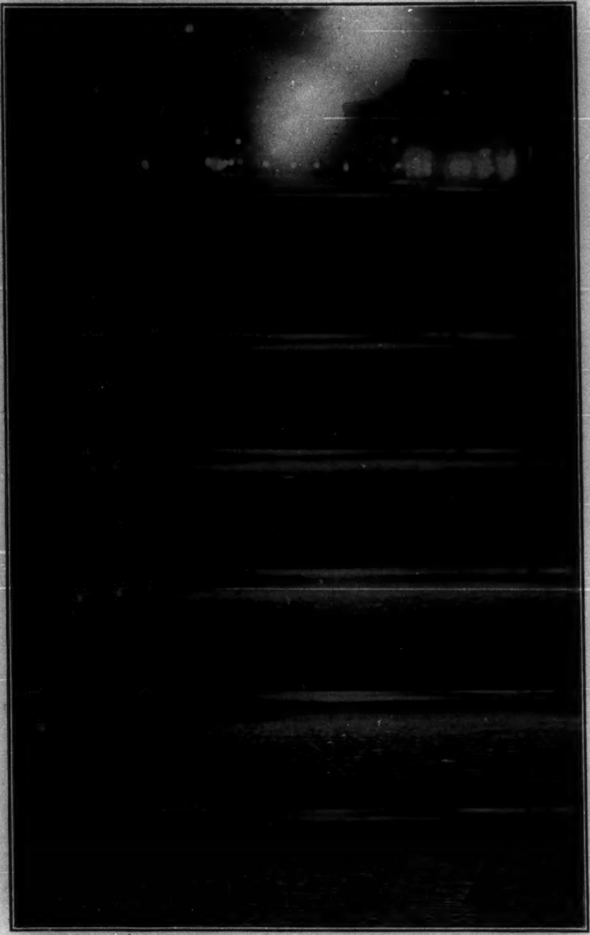
It would appear that in proportion as these three purposes are served the street illumination will be regarded as satisfactory, and it may be concluded that no street lighting installation which serves these three purposes reasonably well can be regarded as unsatisfactory. The weight to be given each will vary in different streets though in a general way it is probable that the purposes are served in the order named. It is possible to install at a low cost a system which will reveal large objects (purpose No. 1) while failing to serve the two other purposes. With increased appropriations, or more efficient illuminants, large objects may be revealed to better advantage and surface irregularities (purpose No. 2) may also be revealed although the third object may not be served. With still larger appropriations and still more efficient illuminants, discernment may be improved and a pleasing appearance for the street (purpose No. 3) by day as well as by night may be had. All three objects may be served when appropriations are adequate.

PROCESSES OF SEEING

In streets at night objects are seen by reason of contour, relief, shadow or color.

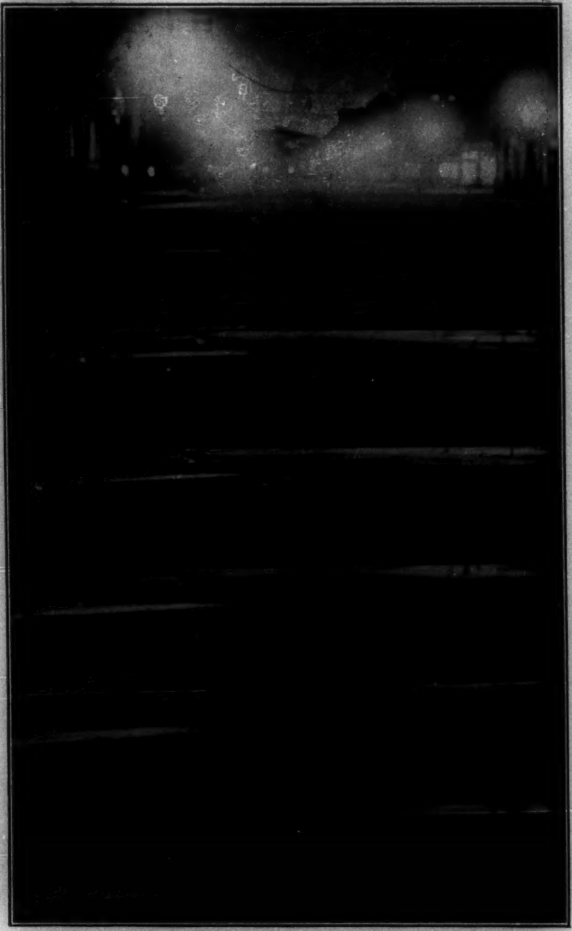
We perceive the contour of objects when they are markedly different in brightness from their background. Since most large objects on the street at night are darker than their background we perceive them usually as silhouettes.

Contrasts in relief are perceived when the exposed surface of an adequately illuminated object presents areas of different



[MILLAR]

FIG. 1A—TEST TARGETS IN SIX REPRESENTATIVE LOCATIONS AS ILLUMINATED BY TWO DIFFERENT SYSTEMS OF LIGHTING. ILLUSTRATING RELIANCE UPON CONTRASTS AND DIFFERENT KINDS OF CONTRASTS PRESENTED TO VIEW



[MILLAR]

FIG 1B—TEST TARGETS IN SIX REPRESENTATIVE LOCATIONS AS ILLUMINATED BY TWO DIFFERENT SYSTEMS OF LIGHTING. ILLUSTRATING RELIANCE UPON CONTRASTS AND DIFFERENT KINDS OF CONTRASTS PRESENTED TO VIEW

reflecting powers, or elements which are more or less favorably inclined with respect to incident light, or elements which lie in the shadow of other elements of the surface.

We may perceive small objects by reason of their shadows occasioned by the interception of sharply inclined rays of light. Shadows of large objects are not always of value in promoting discernment and are often misleading as in case of the shadow of a telegraph pole thrown across the sidewalk.

Color contrasts are not usually relied upon since in installations where discernment is at all difficult, color is usually lost and objects are perceived more readily by other means.

The several kinds of contrast perception are suggested in Figs. 1A and 1B, made from a series of photographs of test targets. These have been located successively in six representative positions between lamps in the street shown in Figs. 8 and 9. Fig. 1A shows the lighting effects by the centrally mounted lamps shown in Fig. 8. Fig. 1B corresponds with Fig. 9. The targets are substantially the same color as the street surface. It is to be noted that those which are most clearly revealed receive the least light and are silhouetted against their background. Those least distinctly revealed receive on the observed surfaces about the same light as their background.

Contrast perception is the ruling visual process with which street illuminations is concerned. To increase contrasts on surfaces to be seen is to better conditions for vision.

SOME CONSIDERATIONS WHICH ARE OFTEN IGNORED

In much of the literature of street illumination, curves of illumination intensity form the principal basis of judgment as to effectiveness. There is a tendency to over-emphasize the importance of incident light to the prejudice of other important considerations. Three of the principal considerations which are not emphasized directly by study of illumination intensity curves are presented in the following paragraphs.

*Silhouette Effect.** When the writer directed attention to the silhouette effect in 1910, there existed but little appreciation of its importance. During the five years which have intervened there has gradually developed a greater appreciation of the extent to which it enters into conditions of visibility in street illumination. Yet its very general applicability even now is unrecognized by some engineers. There is an impression that only in lighting of very low intensity is it the prevailing method of discernment. As a matter of fact the silhouette effect is pronounced whenever there are bright street or building backgrounds. A photographic under-exposure of any street in the daytime shows objects as silhouettes. The casual glance of an automobile driver corresponds roughly with such an under-exposure. The majority of observations of large objects on the streets in our more intensely lighted thoroughfares, especially in the practise of automobile drivers, falls under this heading, because a driver is concerned primarily with avoiding obstacles and usually looks carefully enough only to detect the presence of pedestrians and other objects. Usually he sees these as dark objects silhouetted against the lighter street surface or building surfaces. The pedestrian too obtains distant views of large objects as silhouettes, but as he moves more slowly and approaches objects more closely, he has opportunity for closer observation, and in the more brightly lighted streets supplements discernment by silhouette with actual observation of surfaces in relief.

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*An Unrecognized Aspect of Street Illumination. Millar, Transactions I. E. S., 1910, page 546.

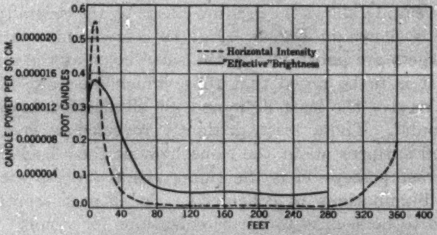


FIG. 3—CURVES OF BRIGHTNESS AND ILLUMINATION INTENSITY

Figs. 5A and 5B show illustrations made from the original silhouette photograph illustrating the importance of this effect in street lighting.

Nature of Street Pavement. Modern streets which require greatest care in lighting are traversed by automobiles. The majority of them are paved with asphalt, asphalt block, wooden block, treated macadam, etc. As a result of automobile traffic such pavements become oiled and polished. The high spots of the pavement then reflect specularly. Fig. 2 is a night view of a part of Columbus Circle, New York City. The pavement is wooden block. The street in the immediate foreground of the picture is not traversed by vehicles. The pavement in the outer ring of the circle, which appears in the middle of the photograph, is traversed by vehicles and has become polished in the manner described. It reflects specularly and its brightness as viewed is due largely to distant lamps.

Figure 3 shows measurements of horizontal illumination intensity and of brightness at the angle of an automobilist's view. The broken line shows horizontal foot-candles as measured on East 80th Street, New York City. This has an ordinary asphalt pavement and is illuminated by multiple enclosed arc lamps 365 feet apart. The continuous line shows brightness values. It will be noted that whereas the foot-candles vary in the ratio of 46 to 1, the brightness varies in the ratio of 8 to 1. This is a street in which automobile traffic forms but a small part of the total traffic.

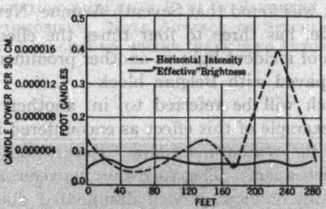


FIG. 4—CURVES OF BRIGHTNESS AND ILLUMINATION INTENSITY

Fig. 4 shows corresponding data for upper Seventh Avenue, New York City, which is a street largely traversed by automobiles. The street is paved with block asphalt; the horizontal foot-candles vary in the ratio of 10 to 1. The effective brightness varies in the ratio of 2 to 1. The impression of uniformity which one derives from a trip through the street is expressed by this brightness ratio rather than by the foot-candles ratio. On this street, which is of the boulevard, central parkway type, there are three lines of lamps. The linear spacing of the lamps is about 125 feet. As the street is fairly level, a great number of these lamps is within view at a given time. The street surface consists largely of small polished areas which reflect specularly. In driving through the street one sees reflected in these small polished areas imperfect images or part images of distant lamps. Notwithstanding the rather wide spacing and marked non-uniformity of illumination intensity, the effect is one of remarkable uniformity of lighting. In driving one looks at the street surface 200 feet or more away, and the surface which he sees is rendered bright by lamps which may be one-quarter, one-half or even one mile away. Consequently the surface between lamps viewed from this angle is almost if not quite as bright as is the surface near or directly under the lamps.

Any street which is largely traversed by automobiles, and which has pavement of the types named above, is likely to appear rather dark because of the oil which is deposited upon it from automobiles. It is, however, a most favorable surface for street lighting purposes because of its tendency to reflect specularly. It was found that Seventh Avenue, New York City described above, has three to four times the effective brightness per lumen of incident light as another prominent thoroughfare which is paved with Belgian block.

Fig. 11 which will be referred to in another connection, an additional example of this effect as encountered in a country road paved with treated macadam. Here lamps are spaced 500 to 900 feet apart. The roadway between lamps, from the driver's point of view, is well illuminated due in part to its specular character.

Recognition of the fact that modern streets are likely to be characterized by more or less of this specular quality necessitates important alterations in some of the theories regarding street lighting which have prevailed in the past and which are held at the present time by some engineers.

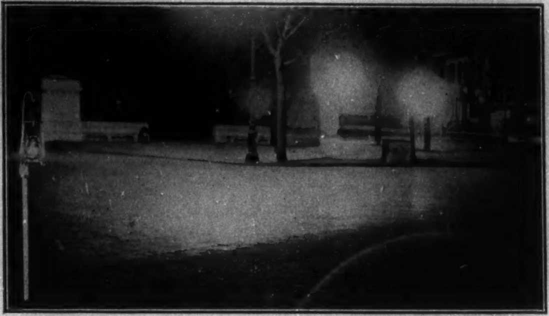
Relation between Lamps and Street Surfaces. The effect of glare in street illumination is dependent primarily upon:

1. The extremes of contrast within view; that is, contrast in brightness between the light source and the illuminated surfaces.

2. The visual angle separating the glaring source from the observed surfaces.

3. The portion of the field of view which is illuminated.

Glare militates against good street illumination, first in decreasing ability to see, and second, in rendering unpleasant the appearance of the installation and the street. Insofar as it reduces visual power it manifests itself in three ways:



[MILLAR]

FIG. 2—VIEW IN COLUMBUS CIRCLE, NEW YORK CITY. NOTE SPECULAR REFLECTION FROM THAT PART OF PAVEMENT WHICH IS TRAVERSED BY AUTOMOBILES. NOTE ABSENCE OF SPECULAR REFLECTION FROM IMMEDIATE FOREGROUND, WHERE THERE IS NO AUTOMOBILE TRAFFIC

[MILLAR]

FIG. 5A—ORIGINAL STREET LIGHTING SILHOUETTE PICTURE. ILLUSTRATING IMPORTANCE OF BRIGHT STREET SURFACE AND SHOWING HOW THE AUTOMOBILE IS DISCERNED BECAUSE THE STREET SURFACE BEYOND IT IS BRIGHT, NOT BECAUSE THE LIGHT FALLING UPON IT RENDERS IT VISIBLE. FOR A DEMONSTRATION OF GLARE SEE FIG. 5B.

[MILLAR]

FIG. 5B—SAME AS FIG. 5A WITH NEARBY LIGHT SOURCE VISIBLE. FOR A DEMONSTRATION OF THE IMPORTANCE OF SEPARATING THE GLARING SOURCE FROM THE OBSERVED OBJECT HOLD THE PICTURE NEARER TO OR FURTHER FROM THE EYES, AS THE DISTANCE FROM THE PICTURE TO THE EYES BECOMES GREATER THE VISUAL ANGLE OF SEPARATION BECOMES LESS AND THE GLARE EFFECT IS MAGNIFIED

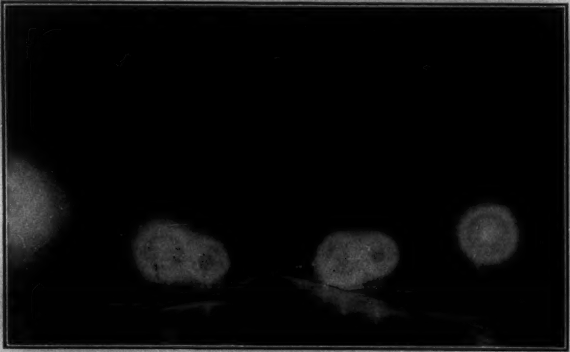


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FIG. 6—SIXTEENTH STREET, WASHINGTON, D.C. 100-CP. MAZDA LAMPS OVER CURBS. NOTE SPECULAR REFLECTION FROM STREET SURFACE NEAR CURBS AND DARK AREA IN MIDDLE OF STREET

Photograph by courtesy W. C. Allen, Electrical Engineer, District of Columbia.

First, actual diminutions in ability to perceive small contrasts in the presence of a bright light source.

Second, distraction of attention as a result of which small contrasts may not be perceived when viewed casually.

Third, a temporary dazzling effect which persists for a few moments after a bright light source is viewed directly.

Figs. 5A and 5B illustrate the effect of glare. In Fig. 5A the nearby light source is removed. In Fig. 5B the presence of the light source distracts attention from the automobile and the view is rendered less pleasant. In fact there is a little discomfort involved in looking at the automobile. Nevertheless if one deliberately dispells the idea of the glaring source from his mind and concentrates on the automobile, it can be seen just as well in either illustration. These pictures further illustrate the importance of securing adequate separation between the light source and the observed object, the distraction due to the light source being greater relatively when the picture is held at a distance from the eye and the visual angle between the source and object is decreased.

If a single brilliant light source, as a bare Mazda C lamp, is located over a dirt road in the country, the glare is very bad. If the lamp is raised to a greater height or moved to one side of the road, or if the lamp is enclosed in a diffusing globe, the glare is lessened. If a number of additional lamps are strung beyond it along the road, the glare is further reduced. If the lamps, instead of being located over a dirt road, are located over a treated macadam road, or better still, over an asphalt road, the glare is less serious. Light-colored buildings along the street also assist in reducing the glare. In short, anything which reduces the contrast between the light source and the road surface, or which increases the illuminated area within view, or which separates the bright light source from the road surface, reduces the effect of glare.

Sweet in 1910* studied that part of the effect of glare which is a measureable reduction in the ability to see, using a single light source in a dark room. He found under these exaggerated conditions that a large reduction in visual power could be traced to the presence of a bright light source close to the center of the field of vision. In 1914† working with others on the

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*"An Analysis of Illumination Requirements in Street Lighting" *Journal of Franklin Institute*, 1910.

†*Electrical Review and Western Electrician*, March 6th, 1915.

campus of the University of Wisconsin, he pursued his researches, and has given preliminary publication to some very interesting results. In this latter research he employed from two to four lamps mounted at various heights and with various spacing intervals over a dirt road about 350 feet long. It is not proposed at this time to enter into a discussion of these tests, but it may be noted that the only conclusions which they can indicate are those which would apply to a short stretch of dirt road. The modifications introduced by street pavements of better reflecting qualities, and by a greater length of illuminated street, have no part in this research. This is a serious limitation, because the effect of glare in street lighting is very largely reduced by each of these factors. The two researches make available valuable information which has its bearing upon street lighting principles. If, however, the data are considered without due regard to the limitations under which the tests were made, there is danger of forming an exaggerated idea of the importance of adopting measures which will reduce the effect of glare by decreasing the brightness of light sources to low values. Since the problem is really one of reducing contrast between the light source and the illuminated surfaces, the more constructive way of accomplishing the desired end is to increase the brightness of the illuminated surfaces rather than to dim the light sources unduly. Excessive brightness of light sources must of course be reduced. It is common experience that a simple diffusing globe accomplishes this reasonably well under most conditions. Too great reduction in the brightness of the light source is unsatisfactory psychologically. We like a bright light source—we are dissatisfied with illumination in which a bright light source is not visible. Therefore the thing to do is to eliminate glare by increasing the brightness of the street surface, and where desirable, that of surroundings, and by reducing the brightness of the light sources moderately throughout the angles at which they are viewed.

With these considerations concerning the importance of the silhouette effect, specular reflection from pavements and glare well in mind, we may proceed to a discussion of the variables of street illumination and of the several factors which the engineer must study in planning a street lighting installation.

ILLUMINATION VARIABLES

The effectiveness of street illumination depends upon the following:

Intensity of Light upon the Street. There is no single measure of intensity which serves all purposes. The average horizontal intensity upon the street surface is most nearly satisfactory.

Brightness of Street Surface. Adopting automobilist's viewpoint as to angle and direction.

Relation between Lamps and Street Surface. Visual angle between the two, and extremes of contrast encountered.

Contrasts Produced on the Street Surface and on Objects on the Street. This is largely a function of the direction of the light.

Portion of Total Field of View Illuminated. This may be affected either by the number of lighted lamps within view or by the area of surface which is illuminated.

Appearance of Installation and of Street by Day and by Night. Lamps, fixtures, light distribution, etc.

INSTALLATION FACTORS

Each of the foregoing variables upon which street lighting effectiveness depends is affected by four or more principal installation factors. These are listed in the first column of Table I, in which the variables are given as column headings. The purpose in presenting this table is to emphasize the complexity of the street illumination problem and to indicate the manner in which the several elements are interconnected. Consider, for example, street surface brightness as a variable in street illumination. The table indicates that brightness depends upon the power of the lighting units, the number of lighting units per mile, the kind of lighting accessories employed, the location of lighting units, the nature of the street pavement and the nature of the surroundings. Alteration in any one of these conditions may influence the brightness of the street and therefore the effectiveness of the street illumination. An engineer who considers any one installation condition must appreciate that his decision may be far-reaching in its influence upon the effectiveness of the lighting, since every installation factor influences a number of these variables. Every street presents its own problems, and the utmost effectiveness of street illumination for a given expenditure is had when each factor is applied with due regard to the relations set forth in this table.

In attempting to discuss these several elements of the problem it is necessary to generalize, and this in spite of the fact that the great differences in streets of the several classes listed

TABLE I. EFFECTIVENESS OF STREET ILLUMINATION.

Installation factors which determine effectiveness	Variables (Influences through which Factors Operate)					
	Intensity of light on street	Brightness of street	Relation between lamps and street surface†	Contrasts on street	Portion of field of view illuminated	Appearance of installation and street, day and night
Power of lighting units	*	*	*	*‡		*
Number of ltg. units per mile	*	*	*	*	*	*
Kind of accessories	*	*	*	*	*	*
Kind of mount						*
Location of lighting units	*	*	*	*	*	*
Nature of pavement		*	*	*		*
Nature of surroundings	*	*	*	*	*	*

†Visual angle and extent of contrast.
‡Visibility not ratio of reflection coefficients.

on page 1431 makes generalization difficult. Nevertheless it is hoped that a general discussion of the influence of each factor upon the several variables will be of value, particularly since it is proposed to note principally those features in which recent experience has suggested some new consideration.

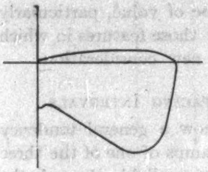
SIZE OF LIGHTING UNITS AND SPACING INTERVALS

Power of Lighting Unit. There is now a general tendency toward the adoption of more powerful lamps of one of the three types listed in Table II. These data are available through the courtesy of the Lamp Committee of the Association of Edison Illuminating Companies; in large measure they are authoritative for lamps of the period stated and equipped as indicated. Of the above illuminants the flame arc lamp and the multiple Mazda C lamp depreciate in candle power 20 to 25 per cent throughout life. The magnetite lamp and the series Mazda C lamps do not change materially throughout life.

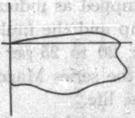
Large versus Small Illuminants. The cluster of lamps employed so largely in "ornamental" or "white way" lighting during the past five years has yielded favor in most recent installations to the single illuminant or less frequently to twin illuminants on one post.

The effectiveness of the light, other things being equal, is dependent upon the choice as between many small lighting units and few large lighting units. In favor of the small illuminants it is urged that greater uniformity results from their use; that they may be mounted lower, thus avoiding shadows from trees, etc.; and it is added that when small illuminants are mounted low, a larger percentage of their total flux is distributed over the street surface. On the other hand, it is argued in favor of large illuminants that they are relatively less costly per mile, and that usually the appearance of a street lighted by them is more pleasing.

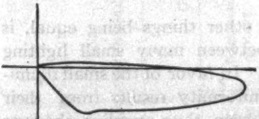
There are two considerations not usually urged in this connection. The first is discussed in more detail under the subject of location of lighting units. Large illuminants are favored from this view-point because they may be placed well out over the middle of the street, where the specular reflection from street surfaces allows the light to be applied in a more favorable direction than that from small illuminants which usually are mounted low over the curb. Fig. 11 is an excellent illustration of the advantageous use of large units in lighting a country



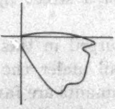
A—Flame Arc Lamp, Clear Globes



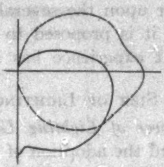
B—Magnetite, Reflector and Clear Globe



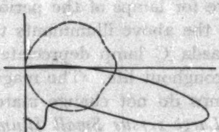
C—Magnetite, Refractor and Clear Globe



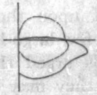
D—Metallic Flame, Reflector and Clear Globe



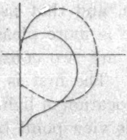
E—Mazda with Diffusing Globe



F—Mazda with Reflector and Refractor



G—Mazda, Radial Wave Reflector



H—Mazda with Diffusing Globe

Distribution characteristics referred to in Table II. Broken line indicates bare lamp

Type	Description of Lamp and Equipment	Mean I			
		Bare			
		Total lumens*†	Terminal watts	Lumens per watt	Tot lumen
Flame arc	G. E. 75/10 amp. a-c. compensator, clear globes, white flame electrode	..	..	..	96
(Various makes of carbon)	Westg. " " " " " " " " "	..	..	..	85
Magnetite and Metallic Flame (Standard type—not the inverted "ornamental" type)	G. E. Magnetite 4 amp., standard electrode, clear globe	..	..	..	29
	" " " 4 " high efficiency electrode, clear globe	..	..	..	46
	" " " 5 " standard electrode, clear globe	..	..	..	57
	" " " 5 " high efficiency electrode, clear globe	..	..	..	70
	" " " 6.6 " standard electrode, clear globe	..	..	..	87
	" " " 6.6 " high efficiency electrode, clear globe	..	..	..	117
	Westg. Metallic flame 4 amp., standard electrode, clear globe	..	..	..	33
	" " " 4 " high efficiency electrode clear globe	..	..	..	41
Mazda C	100-watt multiple	1170	100	11.7	Usual
	200- " "	2513	200	12.5	absor
	300 " "	3767	300	12.5	the lig
	400 " "	5026	400	12.6	
	500 " "	7225	500	14.4	
	750 " "	11787	750	15.7	
	1000 " "	16335	1000	16.3	
	60-cp. 6.6-amp. series	574	44.4	12.9	
	100- " 6.6 " "	1005	73	13.8	
	250- " 6.6 " "	2513	183	13.8	
	400- " 6.6 " "	4021	300	13.4	
	600- " 20-amp. series compensator	6031*	321‡	18.8‡	
	1000- " " " "	10053	504‡	19.9‡	

TABLE II—LIGHT PRODUCING EFFICIENCIES OF MODERN STREET ILLUMINANTS.

ASSOCIATION OF EDISON ILLUMINATING COMPANIES LAMP COMMITTEE DATA ON STREET ILLUMINANTS.

(Arc Lamps Summer 1914—Mazda Lamps Winter 1914)

ean Initial Values				Average throughout life								
Equipped for Street Lighting Service				Bare			Equipped for Street Lighting Service				Approximate life	
Total lumens*†	Terminal watts	Lumens per watt	Distribution characteristic	Total lumens*†	Terminal watts	Lumens per watt	Total lumens	Terminal watts	Lumens per watt	Power factor		
9638	520	18.5	Curve A	..	..	..	8908	523	17.0	73%	130 hr. per trim	Ge constan lumens
8557	480	17.8	Curve A	..	..	..	7288	448	16.3	79%	80 • • •	W withou nal wa
												N with l G. E. C
2991	310	9.65	B or C	No material change in cp. throughout trim has been observed.								• •
4649	323	14.4	• B • C	• •	•	• •	• •	• •	•			• •
5768	390	14.8	• B • C	• •	•	• •	• •	• •	•			• •
7655	371	20.6	• B • C	• •	•	• •	• •	• •	•		Data insufficient to permit assignment.	• •
8708	511	17.0	• B • C	• •	•	• •	• •	• •	•			• •
11774	509	23.1	• B • C	• •	•	• •	• •	• •	•			• •
3330	299	11.1	• D	..	..	..	3655	310	11.8		317 hr. per trim	Westin
4100	306	13.4	• •	..	..	..	..	..	..	..		
												Appro
Usual fixtures and containers			Curve E, F, G	1056	98	10.8	..	..	..	..	Data insufficient to permit assignment. See manufacturers statement.	
absorb from 7 to 35 per cent of			or H	2262	196	11.5	..	..	..	..		
the light given by the lamp.			•	3393	294	11.5	..	..	..	..		
	•		•	4524	392	11.5	..	..	..	..		
	•		•	6509	490	13.3	..	..	..	..		
	•		•	10618	735	14.4	..	..	..	..	•	
	•		•	14700	980	15.0	..	..	..	..		
	•		•	574	45.3	12.7	..	..	..	..		
	•		•	980	74.5	13.1	..	..	..	..		
	•		•	2463	187	13.2	..	..	..	..		
	•		•	3946	306	12.9	..	..	..	..		
	•		•	5554	331‡	16.8‡	..	..	..	..		
	•		•	9047	520‡	17.4‡	..	..	..	..		

*Total lumens = s.c.p. × 4π
1 lumen (L) = 0.08 s.c.p., approx.
†Variations in average candle power have been encountered ranging up to 20 per cent of these values.
‡Including compensator.

road. The lamps are placed 500 to 900 feet apart and 18 to 25 feet high. The effect is good for automobile driving purposes. An example of ineffective use of small illuminants will occur to all who can visualize a wide, wet street with lamps over both curbs. The lighting of the street surface consists of a few bright streaks near the curbs, while the middle of the street is dark. Fig. 6 illustrates this effect upon a dry pavement. As modern street pavements are extended, and automobile traffic increases, the advantages of mounting lamps well over the center of the street tend to increase, and the disadvantages of small illuminants mounted low over the curbs tend to become more apparent.

The second consideration was brought out prominently last year by the Street Lighting Committees of the National Electric Light Association and the Association of Edison Illuminating Companies. It was shown that within reasonable limits, uni-directional light is to be preferred to multi-directional light because it enhances contrasts upon which discernment is dependent. Objects and surface irregularities are seen more surely by uni-directional light than by light coming from a number of directions. From this it follows that, other things being equal, the revealing power of a few large illuminants is greater than that of many small illuminants, especially if the latter are staggered along both curbs.

While these considerations do not clearly indicate the desirability of large units, they do add weight to the arguments in their favor.

LIGHTING ACCESSORIES

Improved Distribution. The most desirable distribution of light depends largely on the nature of the street surface and on the character of the street. Hence there is no such thing as a correct distribution characteristic for all street lighting. The prismatic refractor is successful in providing a distribution characteristic which for a vertical plane conforms to the theoretical requirements as laid down by some engineers. In other forms it will doubtless provide different distributions as required. It is an admirable device so far as re-direction of light is concerned. However, it is objectionable in some forms because of excessive brightness, due to its small size. Also, when combined with the casings with which it is usually employed, its appearance is not attractive. Probably in the evolution of this useful device these objections will be overcome.

The same considerations which underlie the design of the refractor, namely the desire to increase the intensities on street surface at a distance from the lamps, would appear to favor the adoption of assymetrical horizontal distributions whereby light which normally is delivered upon surfaces lying along the sides of the street, is directed upon the street surface. Lighting accessories to accomplish this purpose have been devised but thus far have not received the extensive trial which their theoretical advantages would appear to warrant.

Diffusing Globes. The employment of diffusing globes to decrease brightness of light sources in the street has become more general in recent years. Perhaps the extreme example in the way of increased size of such globes is found in the Washington, D. C., installation of ornamental magnetite lamps, in which 28-inch built up alabaster globes of rather high density are employed. (See Fig. 7). As compared with the use of a clear globe or of a lamp with no globe, a diffusing globe of fairly large size is usually desirable because it improves the appearance of the lighting unit, renders the appearance of the street more pleasing and promotes good conditions of visibility.

It is desirable to secure the best possible balance between low light absorption and good diffusion when selecting diffusing globes. Test data on these two characteristics are of importance and should not be neglected. Because of neglect of simple and inexpensive tests of commercially available glassware, globes are being installed which do not accomplish the purposes in view so well as would other glassware. These either absorb a larger percentage of light than is necessary to secure the desired degree of diffusion, or else diffuse less well than need be, considering the amount of absorption.

Protection for the Eyes. At first glance it would appear that street lighting purposes would be served admirably by a lighting accessory which would concentrate a large proportion of the light flux upon the street surface while directing but little light at those angles which fall near the center of a field of vision in a given installation. However, certain difficulties operate against the success of such a scheme. With practicable mounting heights, spacings have to be short if this is to be successful in illuminating the entire length of the street. The general direction of the light in such an installation is much more largely downward than is usually the case. Wherever there are sufficiently short interval spacings to allow of such

[MILLAR]

Fig. 7—Magnetite Lamps in 28 inch Globes as Used in Washington, D.C.

an installation, there usually exists a requirement for lighting the building fronts. In such installations the relatively high intensities on the street surface, together with the large areas of considerable brightness which present themselves to view, render the glare negligible when ordinary diffusing globes are used. That is to say, in the only installations where it is practicable to use such devices, their eccentric distribution characteristics are unnecessary. Where the surroundings are such that the lighting of building fronts is undesirable or unnecessary, spacings are usually too great to admit of the use of such devices, because their illuminating range is too small. Also considerations of street surface characteristics, discussed elsewhere, suggest that suppression of light at say 80 deg. may do more harm by lessening the pavement brightness than can be compensated by decreased brightness of source.

LOCATION OF LIGHTING UNITS

Comprehended under this heading fall such subjects as height, transverse location and spacing. In most city installations these aspects are standardized for a particular street. In lighting of interurban roadways, lamps are sometimes located in accordance with best judgment, varying considerably in all these particulars.

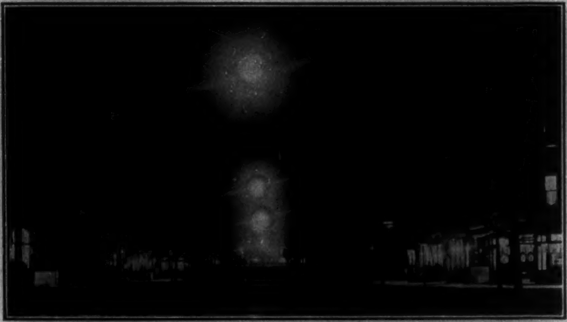
Location Transverse of Street. As between center and curb locations there is a considerable difference. In the first place with lamps located over each curb, the street appears much wider, as is illustrated by a comparison of Figs. 8 and 9, which are alternate test installations of the N. E. L. A. and A. E. I. C. Street Lighting Committees.

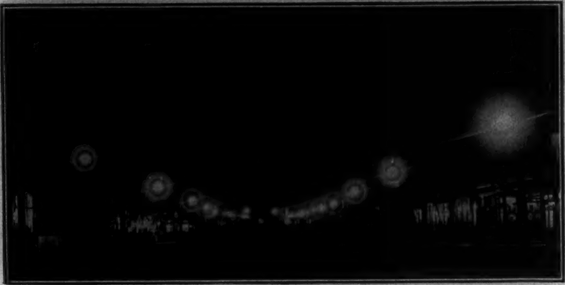
In the lighting of important city streets this is usually a desirable condition. The lamps mounted over the curbs likewise illuminate the sidewalks and the fronts of buildings better (See Figs. 16 and 19). When, however, the lighting of the roadway becomes of first importance, as in streets of the 3*b* class, the best use may be made of the light by locating the lamps as nearly as practicable over the roadway so as to take full advantage of all specular reflection from the street surface. (See Figs. 11 and 6).

Height. In regard to heights of lamps there is also a wide difference in requirements, depending upon the character of the street. In some of the latest practise, powerful lamps are located 14 to 18 feet over the curbs on business streets. These, however, are backed by light-colored buildings and the entire surroundings are so brightly lighted that the glare is not bad. With lamps over the middle of the street the background is usually the dark sky, and usually there are not light-colored buildings to relieve the general darkness. Under these conditions the opportunity for glare to become serious is considerable and it is therefore necessary to locate the lamps rather high. The improvement realized in increasing the height of lamps of moderate power from 18 to 20 feet is considerable, while the improvement in increasing the height from say 27 to 30 feet is not very great. The curve of glare falls off rapidly with increasing separation when the separation between the light source and the observed surface is only a few degrees. Around a lamp which has a dark background there is a zone of halation within which objects tend to become invisible. Once outside this zone, the glare effect falls off less rapidly. It is very important to mount the lamps high enough to insure that the separation from the street surface is at least sufficient to avoid this zone of serious glare.

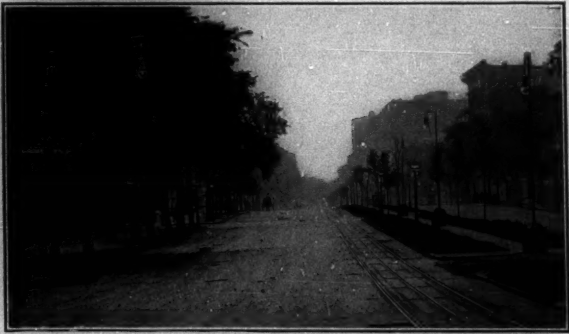
Power of Unit as Related to Glare. Other things being equal, the objectionable effects of glare are greater when the lighting units are more powerful. Hence it is approved practise to mount the more powerful units higher than less powerful units.

Such a lack of separation is responsible for the serious glare illustrated in Fig. 10. An arc lamp is located over the inside of a curve in a road obscuring the roadway beyond. The angle of separation between lamp and roadway is about 3 degrees. Fig. 11 shows the same road but with a lamp located over the outside of the curve and separated from the distant roadway by about 20 degrees when viewed as in driving. It must be recognized that a bright light source obscures its immediate background. This obscuration is greater if the light source is brighter or more powerful, and is less if the background is brighter. In country roads or park drive lighting such obscuration is often very serious. The illustrations in Figs. 10 and 11 indicate one good way of overcoming this difficulty. Recognizing the truth that under such conditions the bright light sources will obscure a certain region of the field of view, the source is so located that the background which it obscures is one which it is not important to see and that the surface which it is desired to see is sufficiently separated from the glaring light source to avoid difficulty.





FIGS. 8 AND 9—CENTER VERSUS CURB MOUNTING IN THE SAME STREET



[MILLAR]

FIG. 12—ADJUSTABLE TEMPORARY INSTALLATION EMPLOYED IN NEW YORK CITY TO DETERMINE BEST LOCATION FOR LAMPS

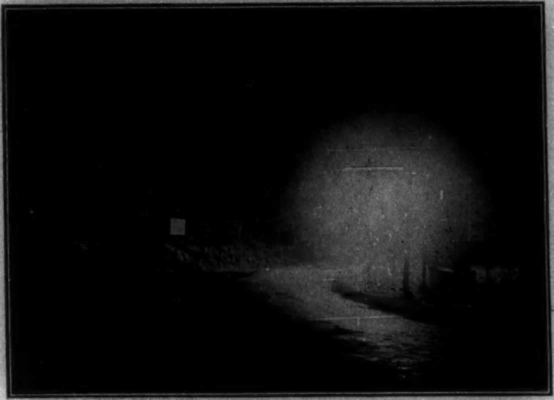


Fig. 10—View of Country Automobile Road. Lamp Wrongly Located on Inside of Curve. Glare Obscures View of Road Beyond

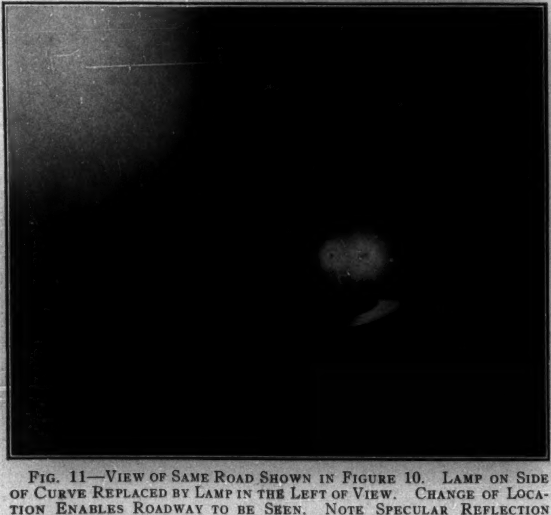


Fig. 11—View of Same Road Shown in Figure 10. Lamp on Side of Curve Replaced by Lamp in the Left of View. Change of Location Enables Roadway to be Seen. Note Specular Reflection from Roadway Due to Lamps 600 and 1000 Feet Away. Excellent Conditions for Driving with Large Illuminants (Magnetite Arc Lamps with Refractors) Widely Spaced [MILLAR]

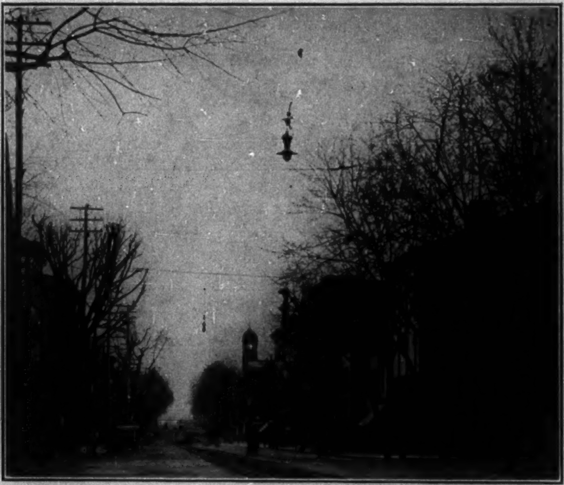


FIG. 13—CARLISLE, PA. 600-CP. MAZDA C LAMPS IN PRISMATIC REFRACTOR UNITS, SPACING 250 TO 500 FT., HEIGHT 18 TO 22 FT.
Photograph by courtesy Edison Lamp Works.

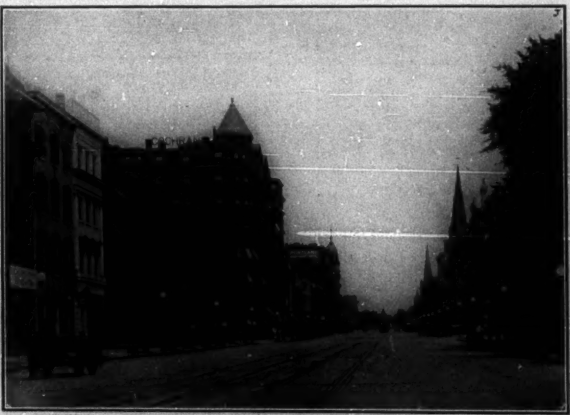
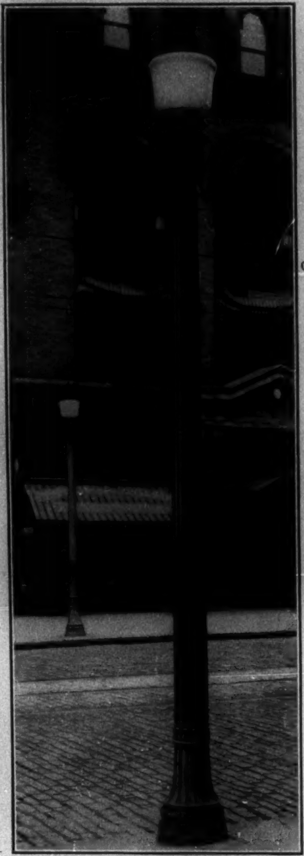


FIG. 14—FOURTEENTH STREET, WASHINGTON, D.C. 100-CP. MAZDA C LAMPS ABOUT 10 FT. ABOVE CURBS, SPACED AT INTERVALS OF 80 FT. ALONG EACH CURB [MILLAR]
Photograph by courtesy W. C. Allen, Electrical Engineer, District of Columbia.

[MILLAR]

FIG. 15—LAKE AVENUE, ROCHESTER. 500-WATT MAZDA C LAMPS, MOUNTED 17½ FT. ABOVE CURB, SPACED AT AVERAGE INTERVALS OF 225 FT.

Photograph by courtesy Rochester Railway and Light Company.



[MILLAR]

FIG. 18—MAIN STREET, ROCHESTER. 6.6-AMPERE MAGNETITE LAMPS. LOCATED 14⅓ FT. ABOVE CURB AND SPACED AT 100-FT. INTERVALS ALONG EACH CURB

Photograph by courtesy Rochester Railway and Light Company.

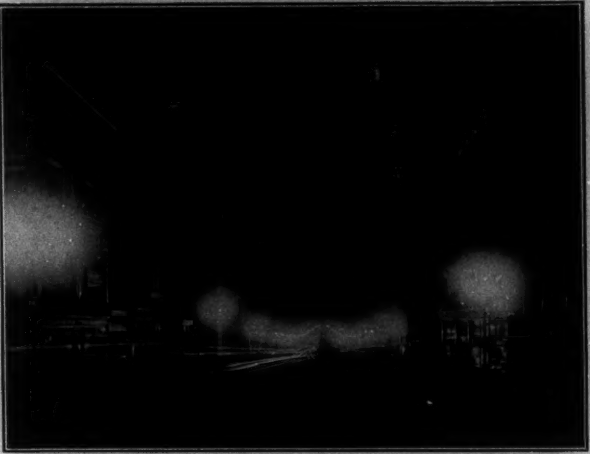


FIG. 16—FIFTH AVENUE, NEW YORK. 400-WATT MADZA C LAMPS ON TWIN POSTS, MOUNTED 19 FT. ABOVE CURB AND SPACED AT ABOUT 100 FT. INTERVALS ALONG BOTH CURBS WITH EXTRA LAMPS AT CROSS STREET INTERSECTIONS

Photograph by courtesy The New York Edison Company

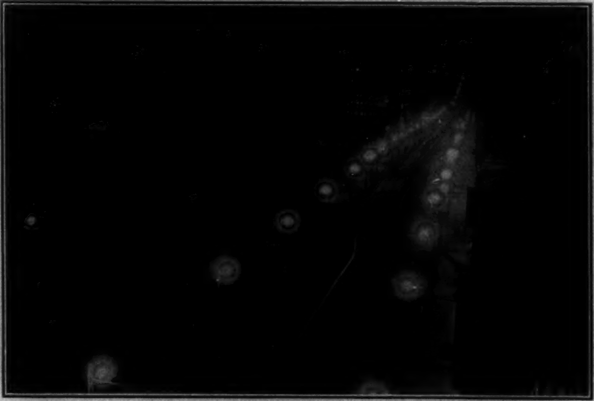


FIG. 17—FEDERAL STREET, PITTSBURGH. SERIES A-C. FLAME ARC LAMPS. WHITE LIGHT CARBONS. LAMPS MOUNTED 24 FT. ABOVE CURB AND SPACED AT AVERAGE INTERVALS OF 69 FT. [MILLAR]

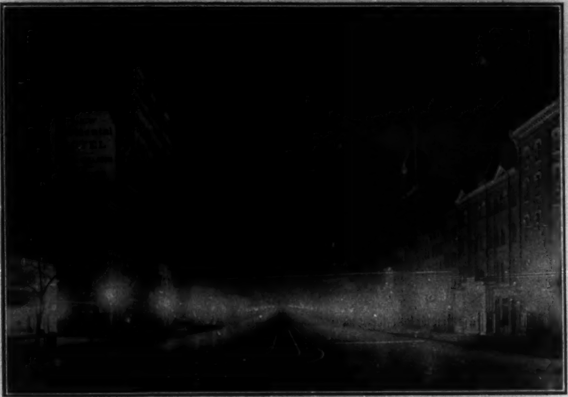


FIG. 19—PENNSYLVANIA AVENUE, WASHINGTON, D.C. 6.6-AMPERE MAGNETITE LAMPS AS ILLUSTRATED IN FIG. 7. MOUNTED 15 FT. ABOVE CURB, SPACED AT 50 FT. INTERVALS ALONG BOTH CURBS [MILLAR]

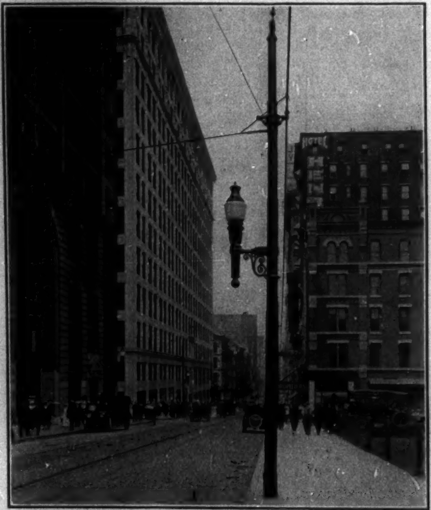


FIG. 20—FIFTH AVENUE, PITTSBURGH. 6.6-AMPERE MAGNETITE LAMPS, MOUNTED 18 FT. ABOVE THE CURB, SPACED AT APPROXIMATELY 80 FT. INTERVALS ALONG EACH CURB [MILLAR]

Spacing. All features of an installation should be treated in such a way as to avoid dark areas between lamps, coupled with low mountings for very bright and powerful lamps. To avoid ineffective results due to multi-directional light which reduces contrasts, spacings need to be greater when the lamps are staggered along both curbs than when they form a line along one side or over the middle of the street. The best spacing would appear to be contingent upon the kind of pavement employed and the nature of the surroundings. All the other factors should be so handled that in driving, one will not encounter the bad condition of a bright light source preventing an adequate view of the surface of the street beyond it.

Fig. 12 illustrates the very excellent practise which is sometimes followed in the city of New York, in locating lamps for street lighting. Lamps which are temporarily installed may be raised and lowered; those mounted from the mast arm post may be placed nearer to or farther from the curb, and those in the center parkways may be moved about at will, the posts being mounted in rock-ballasted barrels. A crew of men locate the lamps in the trial installation as directed by the engineers in charge and the locations which appear to give the best illuminating effects are arrived at. Photometric tests are then made to show the results obtained and to afford a basis for the planning of other installations.

THEORETICAL CONSIDERATIONS WHICH HAVE NOT BEEN DEMONSTRATED

Color. In street illumination where intensities are low, it is believed by some engineers that white light is more effective than yellow light. According to this view, objects are revealed with greater definition; smaller contrasts may be perceived, and there is less suggestion of haziness in the atmosphere when white light is employed. In accordance with the Purkinje effect there would appear to be some basis for this theory, since it is well known that at intensities of the order of 0.01 foot-candles, we see almost exclusively by rod vision and the maximum of the ocular luminosity curve is removed toward the blue end of the spectrum. Whether or not this effect is present in street lighting is one of the interesting subjects of speculation at the present time.

Whether or not white light possesses advantage for low-intensity street lighting due to ocular peculiarities, it is certain that it is preferred by many for high-class street lighting on the ground that it is more suitable, pleasing and dignified than is yellow light. This is perhaps a matter of color association and is surely a matter of taste. It therefore hardly finds place in a discussion of this kind, and is merely mentioned in passing.

"Animation" of Light Source. It has been suggested that the slight fluctuation of light which characterizes arc lamps possesses some advantage for street lighting purposes over the steady glow of the incandescent lamp. So far as the writer knows, no demonstrations have been undertaken, and it has not been shown that this speculation has any basis in fact.

GENERAL STATUS OF THE PROBLEM OF STREET ILLUMINATION

There is an important consideration suggested in the first paragraph of this paper. As more money is expended on street lighting and as more efficient lamps are made available, the intensities of light in streets become greater. As the intensities increase, the requirements for the best possible application of light to promote good visibility conditions become less severe and the requirements for application which improve the appearance of the street become more urgent. From the standpoint of rendering visible the street and objects upon it, the lighting of suburban automobile roads where but little money is available for installation and operation offers the best test for the engineer's skill. In first-class streets we have already progressed to the point where esthetics assume large importance. This does not mean, however, that the problems of street lighting are becoming less difficult; it means simply that the problems are becoming more involved, and broader comprehension of the fundamental principles of street illumination is becoming more essential.

Appendix. In the appendix will be found some statistics of very recent installations in streets of several classes, showing practise in this country as of the early part of 1915. These are accompanied by a few illustrations.

Acknowledgment. The author wishes to express his indebtedness to a number of gentlemen who have kindly supplied some of the photographs for illustrations and the statistics which are utilized in this paper, and who are too numerous to permit of individual mention in this connection.

City and Street	Description of Street Width of roadway in feet	Description of Street Kind of buildings	No. of lighting units	Linear spac in feet along one c
Pittsburgh, Pa. Fifth Avenue.....	36	Business structures	50	Approx.80
Pittsburgh, Pa. Federal Street....	47		90	90
Chicago, Illinois Dearborn Street..	42	Business structures	102	94
Rochester, N. Y. Main Street......	80	Business structures	222	100
Hartford, Conn. Main Street......	90. ft bet. bldg. lines	Business structures	Approx.82 (twin lamp)	112
Washington, D. C. Pennsylvania Av.	109	All kinds	123	100
New York, N. Y. Fifth Avenue. (25 to 58 Sts.)	60	Business structures	200 (2 per post)	150
Corning, N. Y. Market Street		Business structures		100
Rochester, N. Y. Lake Avenue.	50	Residences	56	100
Milwaukee, Wis. Grand Avenue.	92	Business structures		92
New York, N. Y. Seventh Ave (110 to 136 Sts.)	80	Apartment buildings	79	105
Chicago, Illinois Troy Street.	36	Residences		200
Washington, D. C. Sixteenth Street.	50 ft. (160 ft. bet bldg. lines).	Residences	246	120

Installation					
leight n feet	Location	Kind of mount	Lamps	Accessories	Building fronts lighted?
18	Both curbs—opposite	Brackets on trolley poles	6.6-amp. d-c. ornamental luminous arc.	Medium alabaster globes	Yes.
24	Both curbs—staggered	Ornamental posts	a-c. series flame arc. white electrodes	Alba globes	
25	Both curbs—staggered	Ornamental posts	a.-c. series flame arc lamps	Alba globes	Yes.
ft. 6 in.	Both curbs—opposite, main section—staggered outside.	Ornamental posts	6.6-amp. inverted magnetite.	Alabaster globes	
14	Both curbs—staggered	Twin lamp ornamental posts	600-cp. Mazda C.	Novulux, Form 1.	
15	Both curbs—staggered	Ornamental posts	6.6-amp. inverted mangetite—stand. elect.	23-inch segmented Alabaster globe—dense upper, medium lower hemisphere.	Well
19	Both curbs—staggered	Twin lamp ornamental posts	120-volt, 400-watt multiple Mazda C.	Light Carrara globes	Yes.
6 in.	Both curbs—opposite	Ornamental posts	400-cp., 15-amp. Mazda C.	C. R. I. globe and translucent glass reflectors	
3 in.	Both curbs—staggered	Ornamental posts	1000-cp. Mazda C.	Alabaster globes	
10 in.	Both curbs—opposite	Bracket on trolley pole	4.0-amp d-c. series ornamental luminous arc—long life electrodes	Light alabaster globes	Yes.
22	In center of block (on center isle) On curb of intersecting streets at house line of cross street intersection	Ornamental posts	120-volt, 400-watt multitiple Mazda C.	Special ventilated unit—light Carrara globe.	
22	East curb only	Ornamental posts	600-cp. Mazda C.	Alba globes	No.
3 in.	Both curbs—staggered		5.5-amp. series Mazda C, approx. 75 watts	16-inch Alba globes	

[MILLAR]

DISCUSSION ON "THE EFFECTIVE ILLUMINATION OF STREETS" (MILLAR), DEER PARK, MD., JUNE 30, 1915.

G. H. Stickney: There is more difference of opinion as to what is the best practise in street lighting than in any other class of lighting problems. This is due in part to the efforts to classify a wide variety of demands into one or two groups of practise, at the same time putting the extreme emphasis on the cost. Since the disagreement originates with the ultimate lighting effects the lack of agreement as to the methods of producing such effects is not surprising.

The careful analysis presented in Mr. Millar's paper, while not furnishing a solution of the problems, is an important aid in that direction, through clearly defining some of the fundamental facts which have not been generally recognized.

One of the most important divergences in practise is that between the large and small, or the high power and low power lighting units. There seems to be little doubt but that the larger units are generally better for high intensity lighting, and the smaller units more economical for low intensity lighting. The majority of our street lighting problems, however, fall in a class of intermediate intensities, where there is considerable question as to which size of unit will give the best effect for the least cost. Good lighting can be produced from either. The latest tendency seems to be to follow the logical practise of applying units of intermediate power.

We often note the tendency to measure the value of street lighting units in terms of their efficiencies. Although, all else being equal, this would be a fair measure, practically, there are other considerations, such as maintenance cost, adaptability, convenience, appearance, steadiness, etc., which often outweigh a considerable difference in efficiency. This has been illustrated in the transition from the open arc to the enclosed arc, and also in the remarkable spread in the incandescent cluster light, which despite its notorious inefficiency enjoyed an almost unprecedented popularity. This cluster lighting was never viewed with high favor by engineers, and while it is now giving way to more economical and artistic single light posts its former popularity should be recorded as the vote of the public in favor of more ornamental street lighting.

Referring again to the efficiency question, it must be remembered that today the item of electric current consumption used represents only about 20 or 25 per cent of the cost of street lighting service, so that even large gains in efficiency represent relatively small saving. Such gains can, therefore, usually be more profitably taken up in raising the standard of lighting.

The practise of oiling the road and street surface has had a very important relation to street lighting practise. Due to the blackening of the surface, streets which were formerly quite satisfactorily lighted become dull and dingy looking. While the glint effect of such streets is valuable to the automobilist in discerning objects, the black surface absorbs so much light that it is very difficult to produce a pleasing and cheerful lighting effect and much more light is required than in the case of light-colored pavements such as asphalt. It can hardly be expected that the color of pavements will always be selected to facilitate street lighting, but there are many cases in which it would be desirable to consider the street lighting in this connection.

Dugald C. Jackson: This paper is, I hope, a forerunner of other papers to be given at joint meetings of the two societies which are here tonight. Papers of a similar nature have been given by Mr. Millar and other authors before the meetings of the Illuminating Engineering Society, but these papers have not been given the general attention of electrical engineers that the subject warrants.

There are certain features of this paper which impressed me very much and of which I will speak. To begin, the paper refers to the change of attitude of engineers who have to do with street lighting, which has turned them from the enclosed series arc lamp to other types of lamps, and for myself I want to express very great satisfaction in that. I have always believed that the enclosed series arc lamp (especially when operated on alternating current) was one of the mistakes of electrical engineers, and that it arose by allowing the question of the cost of maintenance of a particular machine or piece of apparatus to take the place of consideration of the real effectiveness of its service. Fortunately electrical engineers and others are now turning their attention to more satisfactory illuminants, *i.e.*, more satisfactory when judged broadly, and not solely from the standpoint of how many hours a particular lamp may be burned, or how much labor may be requisite to maintain the structure.

On the other hand, I believe we are likely to be misled by the charm of simplicity in the Mazda lamp and perhaps go too far in utilizing the slightly yellowish light for illuminating important streets. Certainly in the great streets of our cities most individuals are more pleased with the white light than with the yellowish light. There is no question about the possibility of lighting streets and roads with Mazda lamps of large candle power very satisfactorily, but a white light is to most of us more satisfactory, more enspiriting, which is a feature of real importance in a city street in the major business district. The yellowish light, however, probably serves the purpose with full satisfaction in the residence and also perhaps in less occupied business streets.

In my opinion, the question of large versus small units will work itself out. I am convinced that the large units are bound to be used for the important streets of a city. The American cities must, like the foreign cities, become convinced that they need floods of illumination in the regions of great mercantile activity, although they do not need so much light elsewhere. To secure real flood illumination, large lamp units must be used.

There are few objects more graceful and beautiful than a pair of fine white lights on a graceful post, when these lights are properly protected by a fairly large white diffusing globe—the globe being large enough so that any spot in the tremendous amount of light that may be given off may not have any serious effect on the eye. On the other hand, there are cases where sincere effort has been made to get rid of glare according to the mistaken ideas of some man who put up the system, in which rows of large intense lights, with diffusing globes, placed 22 or 24 feet high, 150 to 250 feet apart, down miles of road make a nightmare to travelers on account of the physiological effect of the continuous rows of illuminants on each side, which affect the eye with great discomfort.

One of the most pleasing results of the recent work of illuminating engineers in this country is the attention which is being turned towards the use of graceful lamp posts in the cities. I here avoid the use of the words "decorative posts," because the phrase "decorative lighting" has covered such a multitude of sins by way of ugliness during the last few years. Graceful posts are coming into style. The old mounting of an arc lamp, or some other lamp, on a strip of iron, fastened by a lag screw to a crooked wooden pole, which otherwise carried crossarms and wires, was a poor sort of expedient for supporting the street lights, and if our cities can recognize the worth of, and spend the money necessary to secure graceful posts, I am sure that they will be improved and made happier as places for living.

H. L. Wallau: In the last illustration, which is very interesting, we got two points of view, the wrong and the right. We saw the effect of the lamp placed on the wrong spot, and also saw the effect of the lamp placed on the right spot, but the impression one got was intensified by the fact that the silhouette effect aided the last demonstration; in other words, I am sorry we could not have had three steps, one with the light as originally shown, the second step with the light on the outside of the curve, but in the same direction crosswise to the road, so that the automobile would still have been behind the light. There must be positions on that curve when the oncoming machine would be back of the light, although the light would be on the far side of the curve. The general effect could then be better judged, if we had the two positions to guide us in forming our opinion.

Walter R. Moulton: Referring to the discerning of surface irregularities in streets, I have in mind one interesting example in Baltimore where a water-front street about 100 ft. wide is paved with Belgian block and is lighted by means of luminous magnetite arcs on standards located on safety islands down the center of the street. The rough spots in the street are brought out very distinctly by the shadows cast and also by the increased intensity of illumination on the face presented to the source of light. Because of the nature of the paving, one would hardly expect to find surface reflection, but objects do stand out in silhouette as the granite blocks are worn quite smooth and there seems to be reflection from each individual block. The conditions of this street also illustrate very forcibly the advantage of lights on one side of the roadway only as this condition is quite analagous to such a road.

The effect of street paving on the illumination of a street was very plainly shown when the paving on both Howard and Eutaw Streets in Baltimore was changed from Belgian block to sheet asphalt. The location of luminous arc lamps was not changed, but after the completion of the asphalt paving the lighting condition of the street seemed to be greatly improved. Another interesting effect of street surface is found on the Fallsway, which is a new concrete structure. The entire surface of the road, the sidewalks and a three-foot wall on either side are of concrete and lighted by means of luminous magnetite arc lamps similar to the downtown business streets. This roadway has been in use about nine months and at the present time has absolutely no specular reflection from its surface. The surface of the street, however, seems very well illuminated and the diffuse reflection from the light-colored surface seems to replace specular reflection very well in improving the apparent illumination of a street.

Specular reflection from the surface illumination is important in other outdoor lighting than street illumination. There is a large municipal bathing pool in Baltimore, covering over two acres, which is used at night as well as in the daytime. A number of incandescent lamp standards are located around the pool and also on platforms and pedestals in the center of the pool itself. The general illumination is very good, but ability to see objects on the surface of the water is entirely due to the specular reflection of the lights on the surface.

The excessive brightness of a prismatic refractor unit combined with a high candle power lamp is forcibly illustrated by the difficulty experienced in attempting to photograph such installations. Would this not indicate that such units are brilliant enough to interfere considerably with vision and would it not also seem to point out that their size should be increased?

The commercial value of lavish application of street lighting in the downtown section is well illustrated in Baltimore where over 1000 luminous magnetite arc "white-way" lamps have been installed. At night the business section of the city is made very prominent, it shows up quite strongly from the hilly sections surrounding the city and especially so from the bay. The illumination in the sky from a distance is quite strong and the tall buildings stand out quite prominently against the sky, as the entire face of the building is illuminated.

This latter feature of lighting the building fronts is one that should not be overlooked. The civic buildings, namely the Court House, Post-office and City Hall, are located on three consecutive blocks with wide streets on either side and a plaza on each end and between each building. There are several well-designed office buildings facing the civic buildings. The generous use of white-way lamps in this section makes these buildings quite prominent, especially as they are of light-colored stone, the Court House being of white marble. This section is made really more attractive at night than it is in the daytime.

The esthetic effect of lighting standards or posts throughout the city is quite important. If possible one typical design should be carried out. In Baltimore a special design standard was developed for use with the luminous arc white-way lamps. This same design has been later carried into the residence sections for use with the incandescent lamps and round globes and it has also been carried into the parks. There is a great number of bridges in and around the city and this same design standard has been scaled down and is to be found along the side wall of bridges. Thus there is a harmonious effect produced that is very pleasing. A contrast, however, has been made in Roland Park, an exclusive suburban section, where a special design corner post has been developed, supporting a rustic lantern and also supporting name plates for each street.

The beauty spots of a city can be made prominent and their artistic value greatly enhanced by good street lighting. This is especially true of the small squares and parks to be found in any large city. The bright street lighting surrounding the small park serves as a background against which the dark foliage of the trees shows up very strongly in silhouette. Often a dainty lace-like effect is obtained. The lights in the small park itself serve very well to bring out the beauty of well-formed trees or banks of shrubbery. The variations of light and shade are such as to make the park of untiring interest.

H. H. Magdsick: Mr. Millar has shown clearly what factors determine the effectiveness of the illumination in streets with characteristics typical of our main thoroughfares. For such streets, where the requirements of the driver of a vehicle form the major consideration, the importance of these factors can scarcely be over-emphasized. The discussion would not appear to apply with equal force to most residence districts, which contain a large proportion of the total mileage of streets we have to light, where the safety and convenience of the pedestrian are primary. In serving these the incident light is of far greater importance than in the other class of streets, and the silhouette effect, specular reflection from street surface, etc., are of lesser value. With the funds now available for street lighting in some cities a sufficiently high intensity can be provided at all points on the street to meet these requirements satisfactorily when modern equipment is employed.

It is pointed out in the paper that a bright light source interferes with vision most when the angle of separation between the light source and the surface viewed is small. This effect is to some extent decreased by mounting the unit at a greater height; but considerations of cost, inefficiency and possible obstruction of light, limit this method. It is not generally recognized that much the same result can be secured by the use of prismatic refractor equipment so installed as to direct the maximum c.p.

at an angle of, say, 70 deg. from the vertical, with a considerably reduced intensity at the higher angles, which are viewed when the angle of separation from the illuminated surface is small. The use of this equipment likewise increases the brightness of the street surface. A sufficient intensity is still emitted at the higher angles to satisfy the desire for some brightness in the illuminant and to aid vision when specularly reflected, however, it should be borne in mind that only certain classes of street surfaces reflect specularly to any considerable extent. A study of the streets in many large and small cities has shown that this is a negligible factor in the illumination of a large proportion of the total.

In Table II the average life of series Mazda C lamps under correct operating conditions is given as 1000 hours. It may be noted that while the manufacturers have made guarantees on this basis to cover a large range of street lighting circuits and operating conditions, the actual performance in service as reported in the technical press and at a convention of electrical associations shows that the manufacturers' rated life of 1350 is conservative.

W. H. Pratt: There is an observation which I have made, and which has rather been thrust upon me in reference to street lighting, which I would like to offer for what it is worth. There is a strip of boulevard, some four or five miles long, over which I frequently drive in the evening, and it is illuminated so that it works satisfactorily, so far as the visibility of objects on the road is concerned. The sources of illumination are moderate sized units, spaced very regularly. I find that when somewhat tired, especially with driving over this road, there is a very painful effect, due apparently to the very regular passage of sources of light before the eyes. I wonder if this might not be a factor at times to be considered in determining whether large or small units shall be used. The effect is very noticeable and sometimes is really extremely painful. I can easily understand how under the circumstances a driver might be led to make serious mistakes from that cause. It has a somewhat hypnotic effect, definitely associated with the very regular passage at rather frequent intervals of the light sources through the field of vision.

John B. Whitehead: We have been shown in very convincing and beautiful fashion the importance of specular reflection and the value of a highly reflecting surface in streets and roadways. I notice in all the pictures and in the model that the light sources are still visible, although in many cases the intrinsic brilliancy is reduced by diffusing globes. Nevertheless, the lamps are conspicuous, and I have yet to see a globe which does not in some measure give the disagreeable impressions generally associated with glare. I remember also that when Mr. Millar showed us a lantern slide in which an attempt was made to illuminate a road with concealed sources, the slide indicated that the result was an extremely poor one and not to be compared with that which had been obtained by these methods which he endorses. The question arises, as to whether the distribution curves of various reflectors which conceal the source completely have been studied in their relation to the angle of incidence of the light upon the road surface. In other words, would it not be possible to get a considerable amount of scattered reflection at high angles of incidence?

Peter Junkersfeld: Most of our discussion this evening has been on the illumination of streets, largely from the viewpoint of the pedestrian on the street, or the people using automobiles on the street, or the general illumination of the street. There is one other party whose interest should be considered, and that is the resident along the street, and particularly the resident whose home is opposite some of these high candle power lamps. I have in mind an installation of 3000 or 4000, 600-c.p. type C Mazda lamps in Chicago, installed under the direction of Mr. Ray Palmer. That system of lamps was installed on tubular iron poles, using tubular iron poles also between the poles supporting the arc lamps, and the lighting is very satisfactory from the standpoint of street illumination. A great many complaints, however, have arisen from residents on the street. These high c.p. lamps shine into the second and third story windows, particularly in the summer time, when people do not want their shades down, but want them part way up, so that they can get as much air as possible, and it is quite objectionable from their standpoint. Many complaints have come in and in some places the residents along the street have taken matters into their own hands and painted the sides of the globes. It finally resulted in the passage of an ordinance under which any resident along the street may have a special shade put on the lamp by paying $2 per lamp and $1 per year in advance for the maintenance of the shade. It probably is not sufficient to cover the cost, but serves as a deterrent against unnecessary shading. The lamps are mounted on poles, 25 ft. above the surface of the street.

In other sections of the city where wires are put underground, by common consent the small unit lamps on low poles, 10 or 12 ft. high, have been installed, and that system, from the point of view of the residents, is very much more satisfactory and at the same time gives very good street illumination.

I would add a word to what Mr. Stickney said and possibly also to what Prof. Jackson said, and that is, after all, this whole matter of street lighting must be a matter of compromise. There are many other things which are to be considered besides illumination. The staggering of lamps improves the illumination in many cases. That means, however, considerable increase in cost in installation, whether the wires are overhead or underground, because the wires must cross back and forth across the street, or else there will have to be two lines of poles. There are a great many other factors of that kind that must be taken into consideration in every individual system.

Allen T. Baldwin: In the author's paper, in the paragraph entitled "Power of Lighting Units," reference is made to the depreciation in c.p. of the flame arc and multiple Mazda lamps. A depreciation of 20 per cent to 25 per cent is claimed for each unit mentioned. Insofar as the enclosed type of flame arc lamp is concerned, we have found at our laboratories that 15 per cent to 20 per cent is the average depreciation when measured as the part of the total light flux that is lost through absorption by dirty glassware. For white flame carbon the lower value is nearer the true average.

The light absorption arises from two causes—the etching of the globe and the adherence to the globe of deposits from the arc. The loss of light as the result of etching is the smaller loss of the two. It will probably not exceed 5 per cent to 10 per cent, and a test recently completed on a globe that had been in service over 700 hours showed that it was capable of transmitting 96 per cent of the light transmitted by such globes. The test was made in such a way that this loss was that known to be due to etching alone. Studies have shown that the etching and deposits are least in that part of the globe where it is desirable to have the best light transmission. At the end of the trim life the loss at 80 degrees from the vertical is approximately 5 per cent, while at 10 degrees from the vertical the loss approaches 40 per cent or more.

A comparison of the distribution curves of the lamp at the beginning and end of the life will show that the distribution has been changed in a beneficial way. The deposit in the bottom of the globe acts as a reflecting surface and extends the values along the horizontal at the expense of the light directly along the vertical. These facts point out that the c.p. depreciation is best determined as the loss of total light flux rather than that in any given direction. In reality the increase in efficiency of the lamps gained by eliminating globe etching and deposit would hardly be enough to warrant more than passing attention.

In connection with this subject it is interesting to note that it seems to be an inherent tendency of white flame carbons to give an increase in c.p. as they are consumed, but not to a sufficient extent to counteract the losses just referred to.

L. D. Nordstrum: The point Mr. Jackson brought up in regard to the difference in illumination which might come about when different types of lamps were used, I have had brought to my attention several times in the fact that we have two different installations in Fort Wayne, practically a duplicate form of installation, outside of the light sources used. The old lighting system used the usual type of single unit placed on street corners, usually in the center of the street. Some two miles of the main streets were changed over to what we called ornamental lighting. The poles were placed on the curbs on each side of the street and staggered. They carried a double crossarm with a lamp on each end and a fifth lamp in the center of the pole, with 100-watt Mazda lamps in each globe. This had been installed about a year, and then for about the same distance a new form of lighting was carried out, the same method of pole installation, the poles about the same height, in which we used 4-ampere magnetite lamps. I think that everybody is agreed that the magnetite installation gives much better illumination. Something like seven or eight months ago we had in the evening a very dense fog. These two installations happen to be along the same street, so that they could be compared, and in this dense fog the Mazda light seemed to be entirely blotted out. You could see the Mazda lamps about a block away. Going down that portion of the street where we had the magnetite installation you could see the magnetite lamps strung out along the street a fairly good distance away, for several blocks, at least, whereas with the partially yellow light in the Mazda lamps the illumination was not nearly so effective.

C. E. Stephens (communicated after adjournment): The application of electrical energy in the production of street illumination, to my mind, is one of the most important subjects for consideration by scientific associations. More than any other piece of electrical apparatus, the street lamp is in the public eye. Its importance is not due to the value of this character of load as a market for electrical energy, but to the good or bad indirect effect on the electrical industry, resulting from whether our street lighting installations are good or bad.

Referring to possible improvements in street lighting, it seems to me that greater improvements can be expected in the immediate future, from a more scientific application of available light sources, rather than from radical improvements in the efficiency of available light sources. While the efficiency of light production is extremely low, the power cost is also relatively low when compared to the capital charges for interest and depreciation on the fixtures, transmission, etc., and other items of cost that must be included. A further improvement in efficiency of the source of light would have to be very great in order materially to reduce the present cost of lighting. It is, therefore, a fitting time to analyze carefully the application of the source and to secure the most illumination possible from a given flux or volume of light.

Let us hope that such investigations as are at present being carried on by the electrical industry can be continued, to the end that a standard of street illumination will be set which will secure ample visual discrimination, with comfort, and a mental activity, necessary for safety; and further, that the time will soon come when the doctors will agree.

Preston S. Millar: Professor Jackson has emphasized the possibilities of further intensive study and development in the illumination field. His point appears to be well taken. Those who have visited the Exposition at San Francisco have derived a great deal of inspiration in this connection.

Replying to the question regarding the measurement of effective brightness, it should be stated that the measurements were made about five years ago and were rather crude. After a few trials, we determined the usual angle of an automobilist's view of the street surface, arriving, if my recollection is correct, at two degrees as a typical angle. With a photometer we then measured the brightness of arbitrarily selected patches of street surface at such angle.

Due to the great increase in automobile traffic during these past five years and to the more general adoption of modern pavements, the departure of the brightness curve from the curve of incident light is probably now greater than was found to be typical five years ago.

Mr. Moulton has shown that the prismatic refractors employed in Baltimore are so bright as to spoil the photographic effect by reason of excessive halations. It would appear to be proper to ask if these refractors are not also so bright as to spoil the illuminating effect. In one of the views which he has shown there is an illustration of the lighting of a public building by magnetite lamps along the curb. It is to be observed that the lower stories of the building were lighted nicely, but the upper stories were not well lighted. If these lamps could be moved across the street from the building, securing a greater distance and a better angle of incident light, the general lighting of the front of the building would probably be better.

Mr. Magdsick has dwelt upon the point of view of the pedestrian as opposed to that of the automobilist. I am not sure that these viewpoints are essentially different. In the proposed lighting of a Cleveland street which he has described, I think we arrive at that class referred to in the paper in which esthetic considerations are of first importance. In such problems most of the questions discussed in the paper are of relatively less importance because there is so much light available that application to secure the best visibility is unnecessary.

Dr. Whitehead has suggested that it might be possible to obtain the advantages which come with specular reflection from street surface and still avoid all glare effect. I think he will find that in cases where we have to take advantage of specular reflection, the spacings are so great that light must be allowed to emanate from the lamp at such a high angle that it will produce some glare. When the spacing is so short that the glare effect can be suppressed, there is so much light that ordinary exposure of lamps in diffusing glassware does not produce much glare. The work of Mr. A. J. Sweet may be consulted with profit in this connection.

Mr. Junkersfeld's citation of objection on the part of residents to light on the upper stories of houses is mentioned in the paper as well.

Mr. Baldwin implies that the depreciation during life, shown for flame arc lamps, is a bit too high. We have received criticisms from others that it is a trifle too low. If we may be permitted to average these criticisms, we will conclude that the figures shown in the paper are probably substantially typical.